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## Hydrologic framework of the Santa Clara Valley, California

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## ABSTRACT

The hydrologic framework of the Santa Clara Valley in northern California was redefined on the basis of new data and a new hydrologic model. The regional groundwater flow systems can be subdivided into upper-aquifer and lower-aquifer systems that form a convergent flow system within a basin bounded by mountains and hills on three sides and discharge to pumping wells and the southern San Francisco Bay. Faults also control the flow of groundwater within the Santa Clara Valley and subdivide the aquifer system into three subregions.

After decades of development and groundwater depletion that resulted in substantial land subsidence, Santa Clara Valley Water District (SCVWD) and the local water purveyors have refilled the basin through conservation and importation of water for direct use and artificial recharge. The natural flow system has been altered by extensive development with flow paths toward major well fields. Climate has not only affected the cycles of sedimentation during the glacial periods over the past million years, but interannual to interdecadal climate cycles also have affected the supply and demand components of the natural and anthropogenic inflows and outflows of water in the valley. Streamflow has been affected by development of the aquifer system and regulated flow from reservoirs, as well as conjunctive use of groundwater and surface water. Interaquifer flow through water-supply wells screened across multiple aquifers is an important component to the flow of groundwater and recapture of artificial recharge in the Santa Clara Valley. Wellbore flow and depth-dependent chemical and isotopic data indicate that flow into wells from multiple aquifers, as well as capture of artificial recharge by pumping of water-supply wells, predominantly is occurring in the upper 500 ft (152 m) of the aquifer system. Artificial

recharge represents about one-half of the inflow of water into the valley for the period 1970–1999. Most subsidence is occurring below 250 ft (76 m), and most pumpage occurs within the upper-aquifer system between 300 and 650 ft (between 91 and 198 m) below land surface.

Overall, the natural quality of most groundwater in the Santa Clara Valley is good. Isotopic data indicate that artificial recharge is occurring throughout the shallower parts of the upper-aquifer system and that recent recharge (less than 50 yr old) occurs throughout most of the basin in the upper-aquifer system, but many of the wells in the center of the basin with deeper well screens do not contain tritium and recent recharge. Age dates indicate that the groundwater in the upper-aquifer system generally is less than 2000 yr old, and groundwater in the lower-aquifer system generally ranges from 16,700 to 39,900 yr old. Depth-dependent sampling indicates that wellbores are the main path for vertical flow between aquifer layers. Isotopic data indicate as much as 60% of water pumped from production wells originated as artificial recharge. Shallow aquifers not only contain more recent recharge but may be more susceptible to anthropogenic and natural contamination, as evidenced by trace occurrences of iron, nitrate, and volatile organic compounds (VOCs) in selected water-supply wells.

Water-resource management issues are centered on sustaining a reliable and good-quality source of water to the residents and industries of the valley. While the basin has been refilled, increased demand owing to growth and droughts could result in renewed storage depletion and the related potential adverse effects of land subsidence and seawater intrusion. The new hydrologic model demonstrates the importance of the aquifer layering, faults, and stream channels in relation to groundwater flow and infiltration of recharge.

This model provides a means to analyze water resource issues because it separates the supply and demand components of the inflows and outflows.

## ■ INTRODUCTION

The Santa Clara Valley is a long narrow trough that is a 240 mi<sup>2</sup> (621 km<sup>2</sup>) coastal watershed that borders the southern San Francisco Bay and principally drains parts of Santa Clara and San Mateo Counties, extending ~35 mi (~56 km) southeast from the southern end of San Francisco Bay (Fig. 1A). Most of the basin is characterized by gently sloping topography of coalescing alluvial fans that combine to form the valley floor and coastal tidal lowlands.

The Santa Clara Valley has experienced the typical evolution of land and water-use development in the western United States with a transition from an agriculture and ranching economy to one based on urban services and industry. In the first half of the twentieth century, the valley was intensively cultivated for fruit and truck crops (Fig. 2). Subsequent development has included urbanization and industrialization, and the area is now commonly known as "Silicon Valley." The area underwent extensive groundwater development from the early 1900s through the mid-1960s (Fig. 2). This development caused groundwater-level declines of more than 200 ft (61 m) and induced regional subsidence of as much as 12.7 ft (3.87 m) from the early 1900s to the mid-1960s (Poland, 1971; Poland and Ireland, 1988). As with other coastal aquifer systems, the possibility exists for the combined effects of land subsidence and seawater intrusion with large water-level declines (Tolman and Poland, 1940; Iwamura, 1980).

The San Francisco Water Department started delivering imported water to several north county cities in the early 1950s. In the 1960s, the Santa

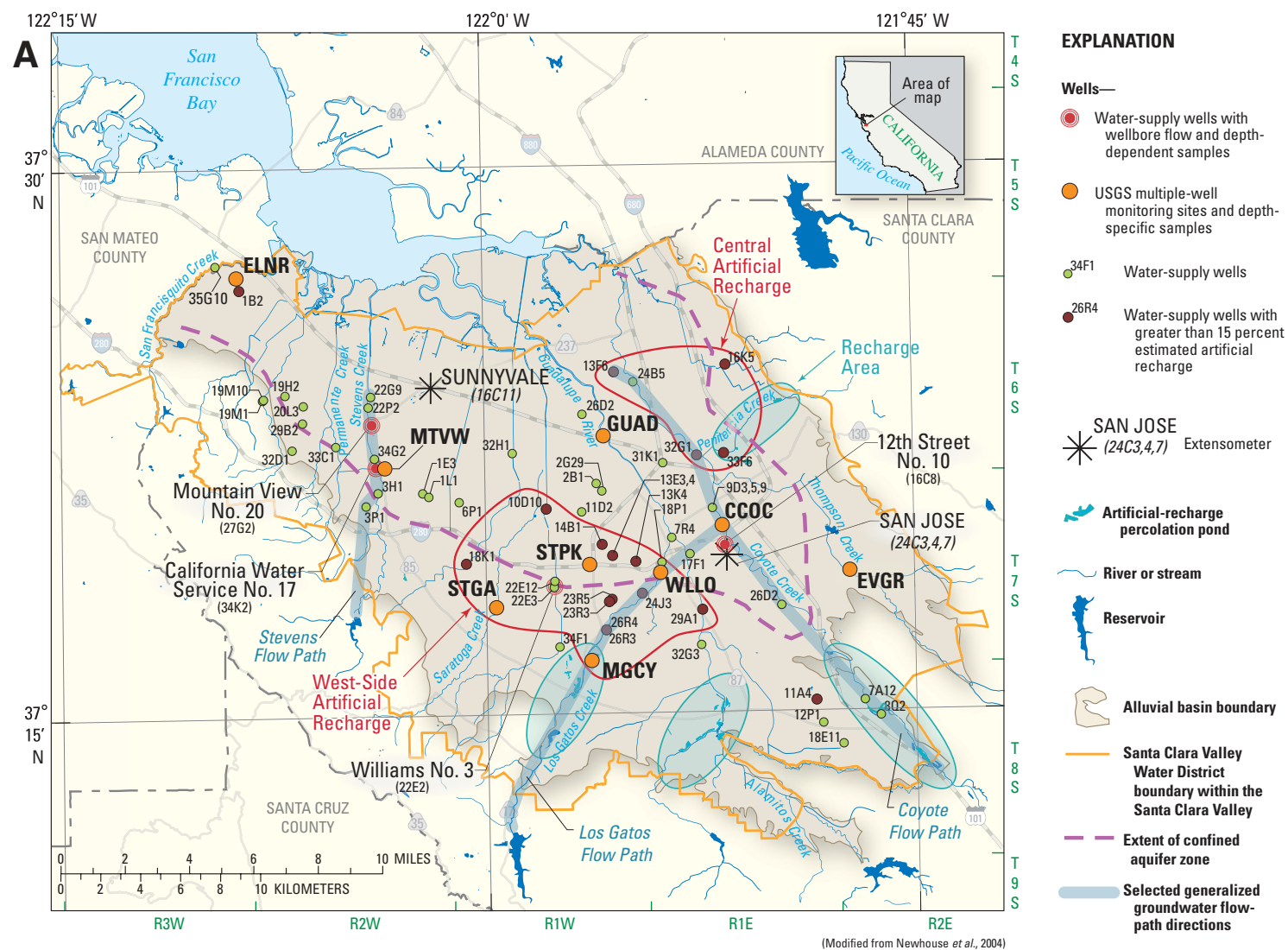


Figure 1. (A) Map showing multiple-well monitoring sites, selected water-supply wells, and extensometers. USGS—U.S. Geological Survey. (Continued on following page.)

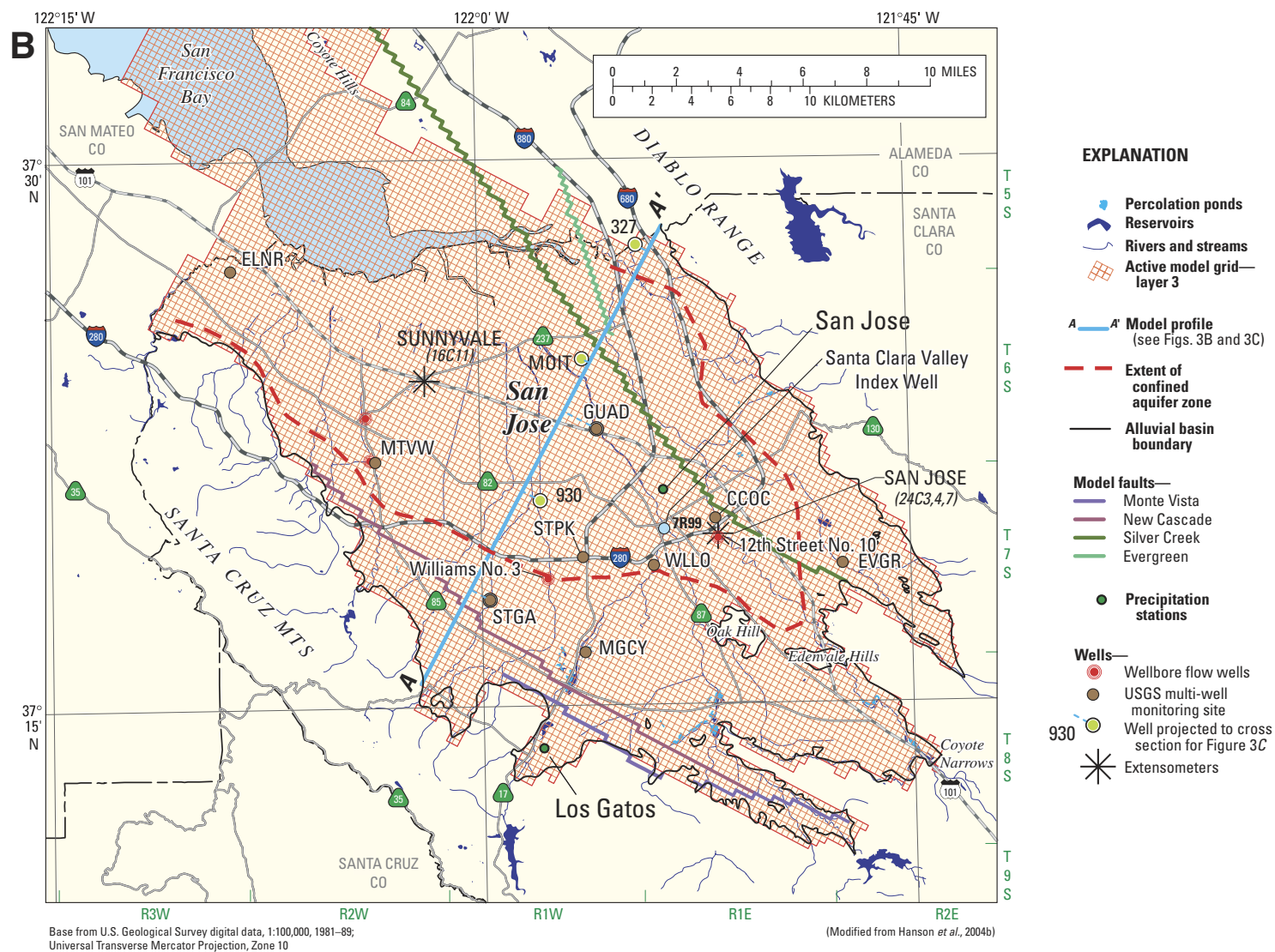


Figure 1 (continued). (B) Map showing model grid, faults, and selected model features in Santa Clara County, California. USGS—U.S. Geological Survey.

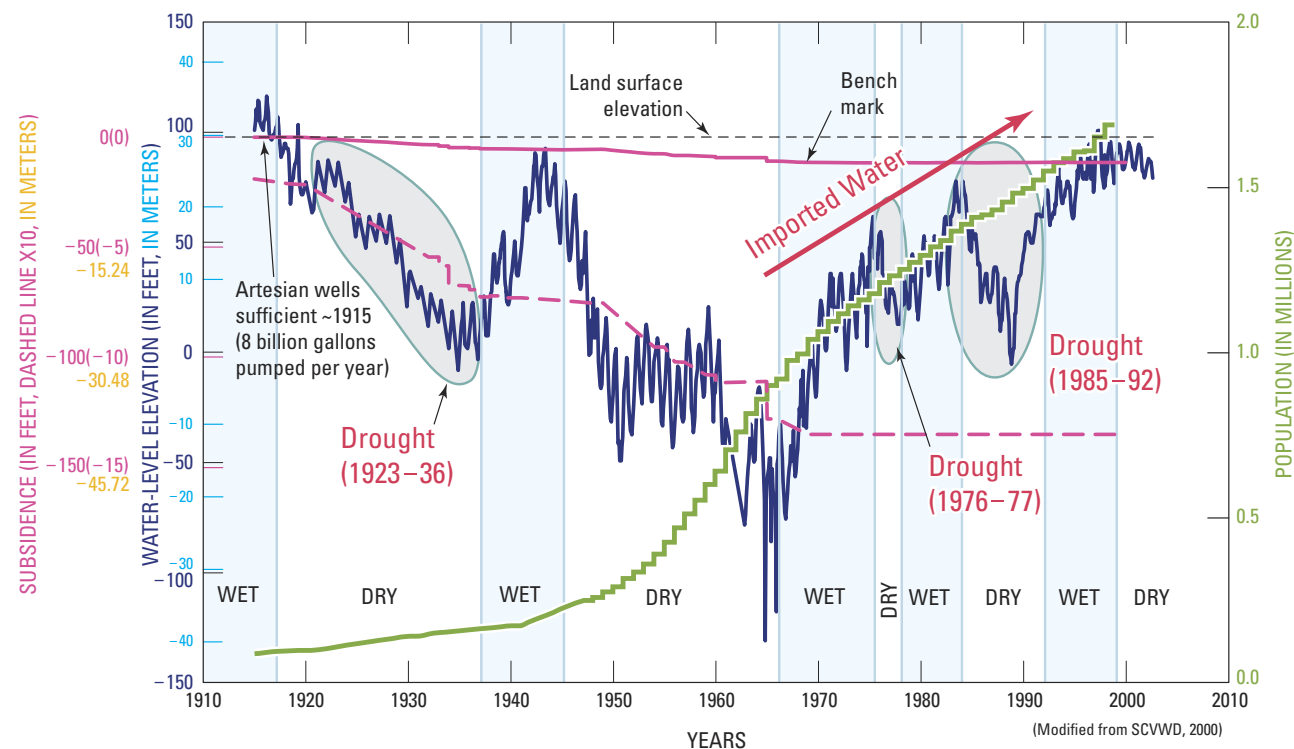


Figure 2. Graph of historical groundwater levels, water use, subsidence, and population for the Santa Clara Valley, California.

Clara Valley Water District (SCVWD) began importing surface water into the valley to help meet growing demands for water and to reduce the area's dependence on groundwater (Fig. 2; SCVWD, 2000). Imported water is treated and either used directly or delivered to ponds used to artificially recharge the aquifer system. Water is imported from California's State Water Project and the federal Central Valley Project. The combination of reduced groundwater pumpage and artificial recharge has caused groundwater levels to recover to near their predevelopment levels, and this, in turn, has arrested the land subsidence (Fig. 2; SCVWD, 2000). Currently, the water purveyors in the Santa Clara Valley, in conjunction with SCVWD, would like to meet the water demand in the basin while limiting any potential for additional land subsidence.

Even though extensive studies have been completed in the Santa Clara Valley, there were no comprehensive three-dimensional hydrologic, geologic, and geochemical data that would allow the delineation of the hydrologic framework that controls the distribution and movement of the water resources in the Santa Clara Valley. Data obtained from nine new monitoring-well sites and various supply wells (Fig. 1A; Hanson et al., 2002; Newhouse et al., 2004), in combination with a detailed groundwater-surface-water model (Hanson et al., 2004b; Fig. 1B) using MODFLOW-2000 (Harbaugh et al., 2000) with the Subsidence Package (Leake and Prudic, 1991), the Streamflow Routing Package (Prudic et al., 2004), and the Multi-Node-Well Package (Halford and Hanson, 2002), were used to further delineate the hydrologic frame-

work. In turn, this framework and model facilitate the development of management strategies and policies that will minimize land subsidence while maintaining a reliable water supply to meet growing demands from water users. This paper summarizes the cooperative studies of the U.S. Geological Survey (USGS) and SCVWD to better define the hydrologic framework and water resources in the Santa Clara Valley.

## ■ HYDROLOGIC SETTING

The hydrology of the Santa Clara Valley includes both surface-water and groundwater flow. Combining imported water with the development of local resources has greatly changed the hydro-



logic setting. The source, age, and movement of water are greatly affected by the geologic framework, climate, and anthropogenic development. The inflow, storage, and outflow of water in the valley are reflected by these influences through the components of the hydrologic budget.

The surface-water system in the Santa Clara Valley includes the natural streamflow network, seven reservoirs, and a system of aqueducts, pipelines, and storm drains. The major streams discharge to the San Francisco Bay through the tidal lowlands along the southern end of San Francisco Bay. Other creeks, such as San Francisquito Creek, which forms the northwestern boundary of the SCVWD, drain directly into the San Francisco Bay. The reservoirs discharge directly into several of the major tributaries and creeks. The aqueducts and pipelines are used to transport imported water directly to treatment plants, where the water is treated and then delivered to artificial-recharge facilities. The storm-drain channels drain additional runoff from the valley floor to the San Francisco Bay.

The natural groundwater flow in the Santa Clara Valley can be characterized as a convergent regional flow system within a basin bounded by mountains and hills on three sides (Fig. 1A). Recharge to the groundwater flow system starts along the mountain fronts and flows toward the center of the basin and toward the southern San Francisco Bay. Many of the predevelopment flow paths have been modified by pumping centers characterized by groups of wells in localized well fields that have resulted in subregional cones of depression and related convergent flow paths. Discharge from the groundwater flow system occurs as pumpage, underflow, base flow to streams, and evapotranspiration.

### Hydrogeologic Structure

The regional groundwater flow systems can be subdivided into upper-aquifer and lower-aquifer systems. The aquifer layers are relatively flat lying and range from 10 to 200 ft (3 to 61 m) in thickness. The aquifer layers are separated by thin, low-permeability, fine-grained layers that result in as much

as 10 ft (3 m) of vertical head differences between aquifer layers (Newhouse et al., 2004). The effective base of the groundwater flow system is relatively shallow compared to other coastal basins, ranging from ~500 to 900 ft (~152 to 274 m) below land surface. The groundwater flow system also is affected by the presence of faults that may potentially act as hydrologic flow barriers, by a subcropping bedrock high of serpentinite plunging northwest from Oak Hill, and by lithofacies that may represent regions of enhanced or reduced permeability (Figs. 3A and 3B). The new groundwater flow model simulates the flow of groundwater and surface water throughout the alluvial aquifer system (Fig. 3A). For modeling purposes, the sediments were previously grouped into six layers that represent the shallowest recent aquifer of the Holocene-aged deposits, which is underlain by the confining beds of the Bay Muds. Below the confining layer, there are three more layers that represent the remainder of the Pleistocene-aged sediments of the upper-aquifer system and an additional layer that represents the Pliocene–Pleistocene-aged sediments of the lower-aquifer system (Fig. 3B).

The upper-aquifer system is composed of the Shallow aquifer, which is coincident with Holocene-age sediments, and the middle-to-late Pleistocene-age sediments (Fig. 3A). The upper-aquifer system contains some water that recently (less than 60 yr B.P.) entered the groundwater system as recharge and some water that entered the system as much as 2500 yr B.P. (Hanson et al., 2002; Newhouse et al., 2004). The lower-aquifer system is composed of sediments of early Pleistocene or Pliocene age and contains water that entered the groundwater system more than 10,000 yr B.P. (Hanson et al., 2002; Newhouse et al., 2004). The regional aquifer system is underlain and surrounded by the relatively impermeable bedrock. The Santa Clara Formation, which outcrops along the margins of the valley, is not present in the interior parts of the valley (Andersen et al., 2005; Wentworth and Tinsley, 2005; Wentworth et al., 2015). The Santa Clara Formation was not identified initially in many deeper wells (Tolman and Poland, 1940) and has not been encountered in the recently completed multiple-well monitoring sites completed by the

USGS in cooperation with SCVWD. Therefore, the depth of the alluvial-aquifer system and the depth of the effective groundwater flow system were uncertain in some parts of the valley prior to the ongoing studies. Sequence stratigraphic analysis and related hydrostratigraphy are part of the USGS studies (Jachens et al., 2001) that have further delineated the geologic and hydrogeologic framework (Wentworth et al., 2010, 2015; Langenheim et al., 2014).

Faults also control the flow of groundwater within the Santa Clara Valley and subdivide the aquifer system into three subregions, with a western Cupertino basin, a central graben-like feature, and the eastern Evergreen basin (Hanson et al., 2004b; Stanley et al., 2002; Langenheim, et al., 2013). The faults identified as part of this study that affect the flow of groundwater include the Silver Creek and Evergreen faults in the eastern part of the valley and the Monte Vista and New Cascade faults in the western part of the valley (Figs. 1A, 1B, 3A, and 3B).

In addition to these features, coarse-grained facies that are subparallel to and beneath selected stream channels potentially enhance permeability, and fine-grained facies adjacent to other selected stream channels, such as San Tomas Aquino Creek, reduce permeability (Hanson et al., 2004b). Coarser-grained facies also are present down the axis of the valley subparallel to and on the western side of Silver Creek fault. These facies, in combination with this fault, form a partial flow barrier that controls the shape and extent of the land-surface deformation down the axis of the valley, estimated with interferometric synthetic aperture radar (InSAR) images (Galloway et al., 2000).

The regional groundwater flow system within the Santa Clara Valley also can be divided into two onshore subregions that represent the confined and unconfined parts of the aquifer systems (Fig. 1). The area has undergone extensive groundwater development in the shallow upper aquifers (locally referred to as the “upper aquifers”), which are composed of recent, Holocene-age, and Pleistocene-age fluvial deposits and marine estuarine deposits (locally referred to as “Bay Mud” and “Old Bay Mud”; Fig. 3A). Extensive groundwater

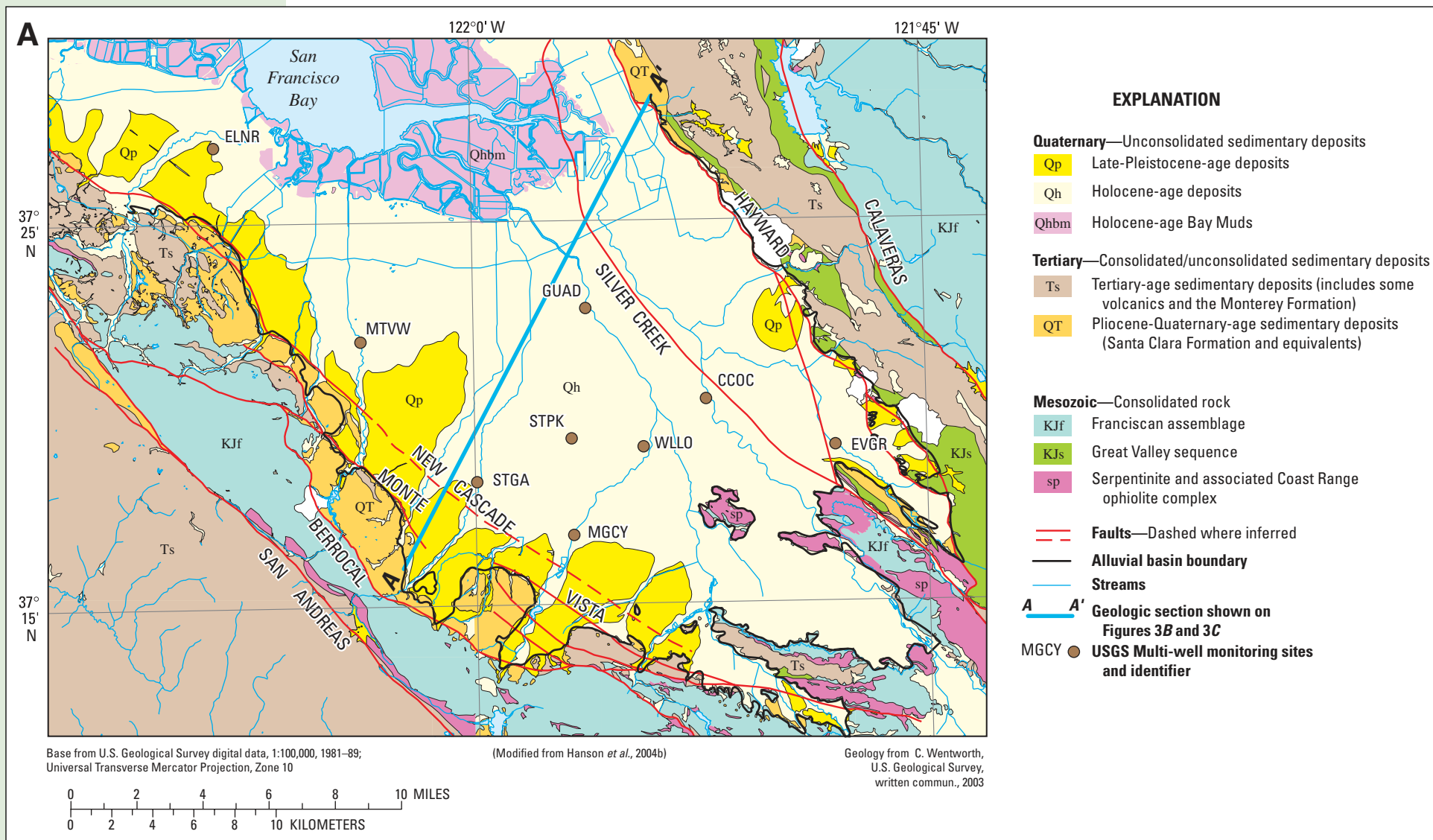


Figure 3. (A) Map showing the geology and selected structures that affect the movement of water. USGS—U.S. Geological Survey. (Continued on following page.)

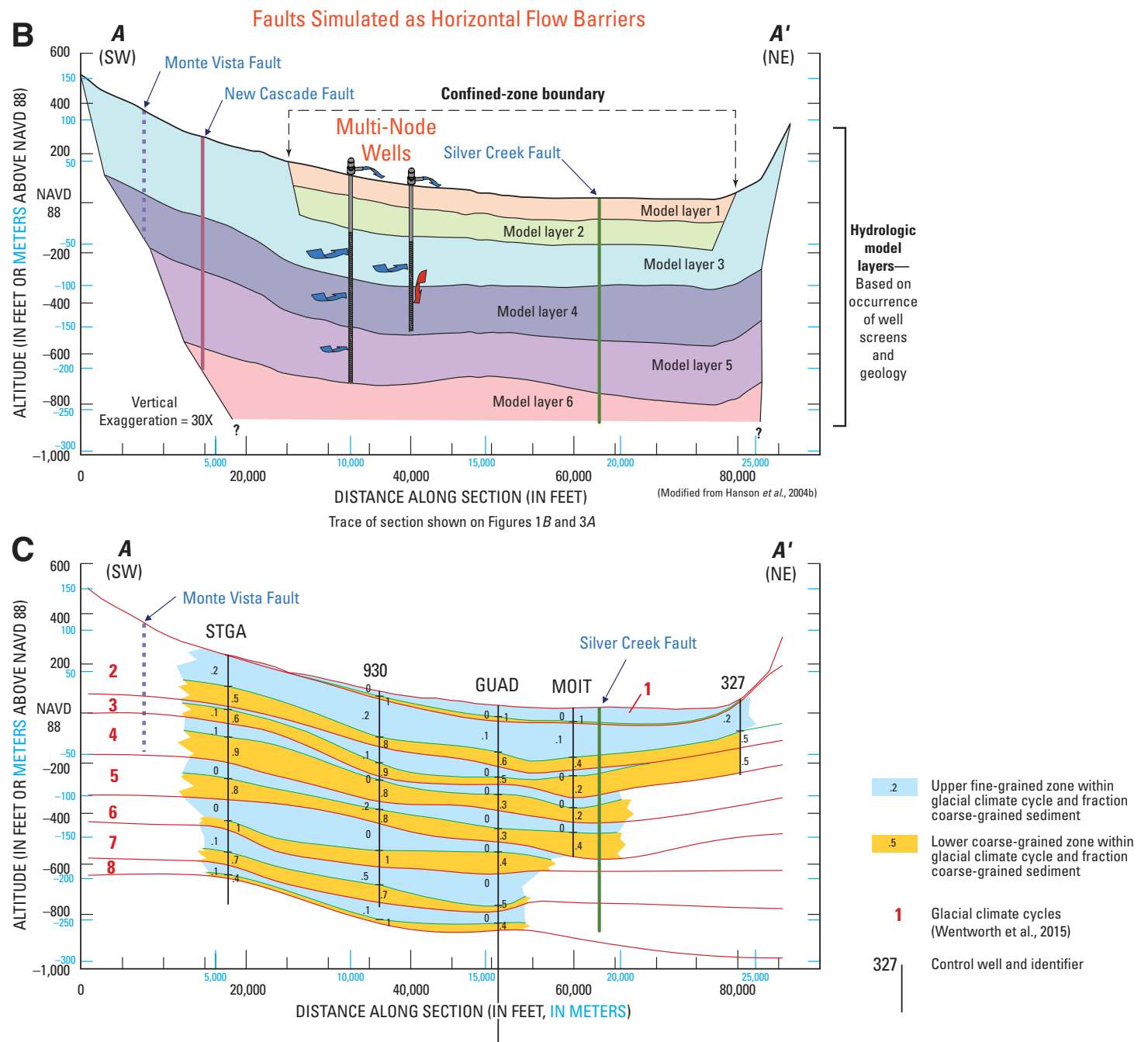


Figure 3 (continued). (B) Cross section of previous models, and (C) new sequence stratigraphic layers across the Santa Clara Valley, California. USGS—U.S. Geological Survey.

development also has occurred below these deposits in the Pleistocene- and Pliocene-age fluvial deposits, which locally are referred to as the “lower aquifers” (Fig. 3A). The alluvial deposits that form the regional aquifer systems are unconformably underlain by Pliocene-age deposits of the Santa Clara Formation in the valley margins, Tertiary-age sediments that include the Miocene-age parts of the Monterey Formation in the Cupertino subbasin, and Tertiary-age serpentinite and Great Valley Sequence in the Central and Evergreen subbasins (Fig. 3B; Wentworth et al., 2010; Langenheim et al., 2014). These underlying deposits form the relatively impermeable base of the regional aquifer systems. The alluvial aquifer systems are composed of a complex sequence of layers of fluvial sand and gravel and fluvial fine-grained silt and clay (California Department of Water Resources, 1967; Wagner et al., 1990; Wentworth, 1997; Wentworth and Tinsley, 2005; Wentworth et al., 2004, 2015; Knudsen et al., 2000). These layers represent the glacial climate cycles that resulted in the eight cycles of sedimentation over the past 718,000 yr (Fig. 3B; Wentworth et al., 2015). The confining units in the upper part of the latest cycles represent a regional inundation of the valley during the persistent tectonic subsidence occurring over the past 718,000 yr (Wentworth et al., 2010, 2015). Each cycle represents a fining-upward sequence of predominantly fluvial and alluvial sedimentation that results in coarser-grained basal layers and fine-grained upper layers. These coarser-grained layers represent the aquifers, and the fine-grained layers represent the confining units or aquitards and interbeds. The water pumped as groundwater principally flows to the wells through the aquifers. The water that contributes to land subsidence mostly comes from the compaction of the aquitards. The aquitards also restrict the vertical flow of water. The layering is more pronounced in the last four glacial cycles, which include the upper confining units known as the “Bay Muds” (Fig. 3B). Outside the extent of these fine-grained confining units (Fig. 1B), the uppermost aquifer systems are considered unconfined, where changes in groundwater storage are from filling and draining of pore spaces in the alluvial sediments at the water table.

## WATER-BUDGET COMPONENTS

Regional groundwater flow within the multiple aquifers of the Santa Clara Valley is the result of natural and artificial inflows and outflows. Groundwater flow converges from the edges of the elliptical basin along the mountain fronts, where a combination of natural and artificial recharge enters the aquifers, toward the pumping centers in the central part of the basin and toward the southern San Francisco Bay as underflow.

Groundwater inflow occurs as recharge, subsurface flow along the northern coastal boundary of the southern San Francisco Bay, and water derived from aquifer and interbed storage. Groundwater recharge includes areally distributed infiltration of precipitation in excess of runoff and evaporation, streamflow infiltration, artificial recharge, and losses from water-transmission pipes. Groundwater outflow occurs as evapotranspiration, stream base flow, discharge through pumpage from wells, and subsurface flow to the San Francisco Bay.

The total groundwater inflow and outflow is simulated at  $\sim 225,500$  acre-ft/yr ( $\sim 278.15$  Mm<sup>3</sup>/yr) for the period 1970–1989 and is simulated at  $\sim 205,300$  acre-ft/yr ( $\sim 253.23$  Mm<sup>3</sup>/yr) for the period 1970–1999 (Hanson et al., 2004b). Overall, the simulated net change in storage increased by  $\sim 189,500$  acre-ft/yr ( $\sim 233.74$  Mm<sup>3</sup>/yr) for the period 1970–1999, which represents  $\sim 1.5$  yr of the 1970–1999 average pumping. The changes in groundwater flow and storage generally reflect the major climate cycles and the additional importation of water by SCVWD, with the basin in recovery since the drought of the late 1980s and early 1990s. On average, an accretion of  $\sim 7\%$  of the water in the flow system was simulated as going back into groundwater storage over the period 1970–1999 (Fig. 4A).

The average total recharge rate from natural and artificial recharge and from streamflow infiltration for the revised model for the entire simulation period of 1970–1999 was  $\sim 157,100$  acre-ft/yr ( $\sim 193.78$  Mm<sup>3</sup>/yr), which represents  $\sim 59\%$  of the inflow to the groundwater flow, and  $\sim 72\%$  of the inflow with respect to net pumpage (Fig. 4A). The average rate of artificial recharge of  $\sim 77,600$  acre-ft/

yr ( $\sim 95.72$  Mm<sup>3</sup>/yr) represents  $\sim 36\%$  of the inflow to the groundwater flow system and about one-half of the outflow as pumpage (Fig. 4A). Most of the simulated recharge infiltrates and flows through the uppermost layers (i.e., model layers 1 and 3) of the aquifer system. An average of  $\sim 3\%$  of the simulated streamflow infiltration is rejected back to the streams and flows to San Francisco Bay (Fig. 4A).

The average rate of pumpage of  $\sim 133,400$  acre-ft/yr ( $\sim 164.55$  Mm<sup>3</sup>/yr) for the period 1970–1999 represents  $\sim 69\%$  of the outflow from the groundwater flow system. Total recharge was 11% greater than total pumpage during this period. Most of the water that flows to the deeper model layers is occurring through wellbores, with wellbore flow representing 19% of the total groundwater flow between model layers.

The changes in groundwater flow generally reflect the major climate cycles and the additional importation of water by SCVWD (Fig. 4B). The basin has been in recovery since the drought of the late 1980s and early 1990s, as demonstrated by the trend toward negative change in storage (that is, water going out of groundwater flow and back into groundwater storage; Fig. 4B). While the imported water has declined slightly with some year-to-year variation on the order of 25,000–50,000 acre-ft/yr (30.84–61.67 Mm<sup>3</sup>/yr), the water-level recovery and related increase in groundwater storage generally are driven by a substantial decrease in groundwater pumpage since 1989 (Fig. 4B). The water derived from interbed storage has been near zero (Fig. 4B) and represents a small percentage of the total change in storage over the period of simulation (Fig. 4A). Because so much of the valley has been urbanized, the evapotranspiration has been a small and relatively constant component of the water budget (Fig. 4A). The streamflow infiltration shows some climatic variability and has remained between 20,000 and 50,000 acre-ft/yr (24.67–61.67 Mm<sup>3</sup>/yr) through the 29.75 yr period (Fig. 4B). The outflow at the San Francisco Bay (net general head boundary [GHB]) has shown a small but steady increase during the basin recovery (Fig. 4B). This is consistent with most of the recharge infiltrating and flowing through the uppermost layers of the aquifer system.



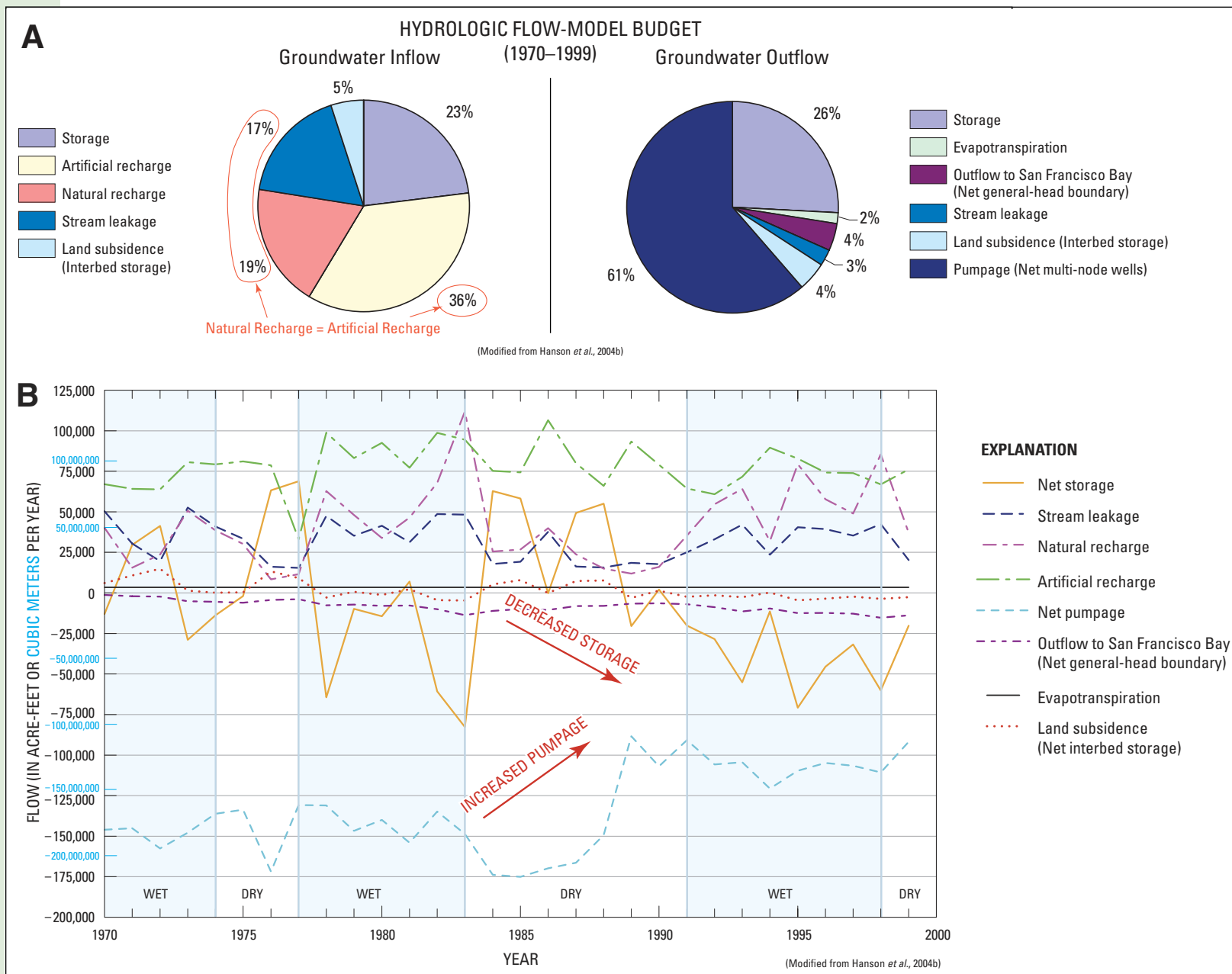


Figure 4. Graphs showing (A) percentages of inflow and outflow components of the hydrologic budget for the period 1970–1999 and (B) time series of inflow and outflow components of the groundwater flow system for the period 1970–1999, Santa Clara Valley, California.

## Role of Climate Cycles

Climate cycles not only have affected the cycles of sedimentation during the glacial cycles over the past million years (Wentworth et al., 2010, 2015), they also affect the flow of water. Both natural and anthropogenic inflows and outflows in the coastal watersheds and aquifer systems are affected by major interannual to interdecadal climate cycles (Fig. 4B; Mantua et al., 1997). Even with the importation of water, storage depletion and related increased pumpage occur during dry periods, and storage accumulation with reduced pumpage occur during subsequent wet periods (Fig. 4B). The Mediterranean-style climate results in 89% of the rainfall occurring between November and April, which is typical of the seasonal climate cycle in California coastal areas. Average annual precipitation is ~14.5 in (~36.8 cm) in the City of San Jose (1883–2002), ~23 in (~58.4 cm) near Los Gatos (1964–2001) in the intermediate altitudes of the Santa Clara Valley, and more than 50 in (127 cm) in the surrounding mountains. The cumulative departure of rainfall in San Jose during the past century indicates a persistent set of multiyear wet and dry periods—some relatively long periods (10–21 yr), and some shorter periods (2–9 yr; Fig. 5). These wet and dry periods also are related to major droughts and flood events (California History Center, 1981). Although wet years may occur in dry periods and dry years may occur in wet periods, the historical climate generally can be categorized into six climate cycles that represent 14 wet and dry periods determined from the cumulative departure of annual precipitation in San Jose (Fig. 5). The periodicity of the precipitation is very similar to some of the tree-ring indices from the coastal Santa Lucia Range to the southeast of Santa Clara Valley (Fig. 6). The tree-ring indices, with a longer period of record (1830–1995), also contain larger cycles of ~48 and 32 yr, respectively.

These wet and dry periods are composed of variations that are driven collectively by the cycles of the El Niño–Southern Oscillation (ENSO; 2–6 yr), the North American monsoon (7–10 yr), and the Pacific Decadal Oscillation (PDO; 10–25 yr; Fig. 5; Mantua, 2006; Hanson et al., 2004a, 2006). Over

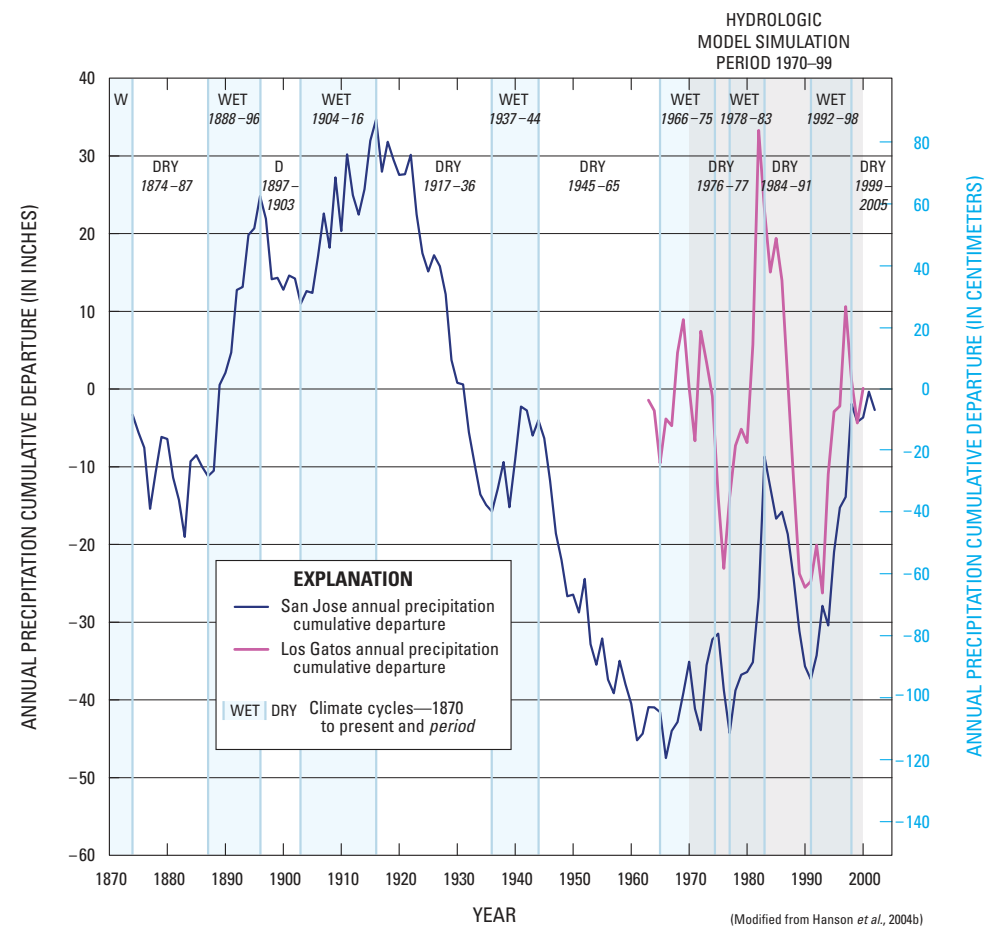


Figure 5. Graph showing cumulative departure for precipitation in San Jose and Los Gatos, California.

92% of the variation in precipitation measured in San Jose can be explained by periodic variation that is in alignment with these major climate cycles. These climate cycles indirectly have driven the supply and demand of water resources. As these climate cycles come in and out of phase with each other, the differences in climate cycles have an additional effect on the seasonal cycles, which can result in reduced streamflow infiltration, varied supply of artificial recharge and additional pumpage, and land subsidence. For example, the wet periods

can result in extreme recharge and streamflow flooding events such as the floods of 1862, 1895, 1911, 1955, 1982–1983, and 1997–1998. The dry periods, such as 1976–1977 and 1984–1991, can result in reduced delivery of imported water and reduced recharge, as well as increased pumpage and additional land subsidence (Fig. 4B).

Spectral analysis of the major interannual- to interdecadal-scale periodic changes in selected hydrologic time series (Hanson et al., 2004a, 2006) shows that tree-ring indices, precipitation, ground-

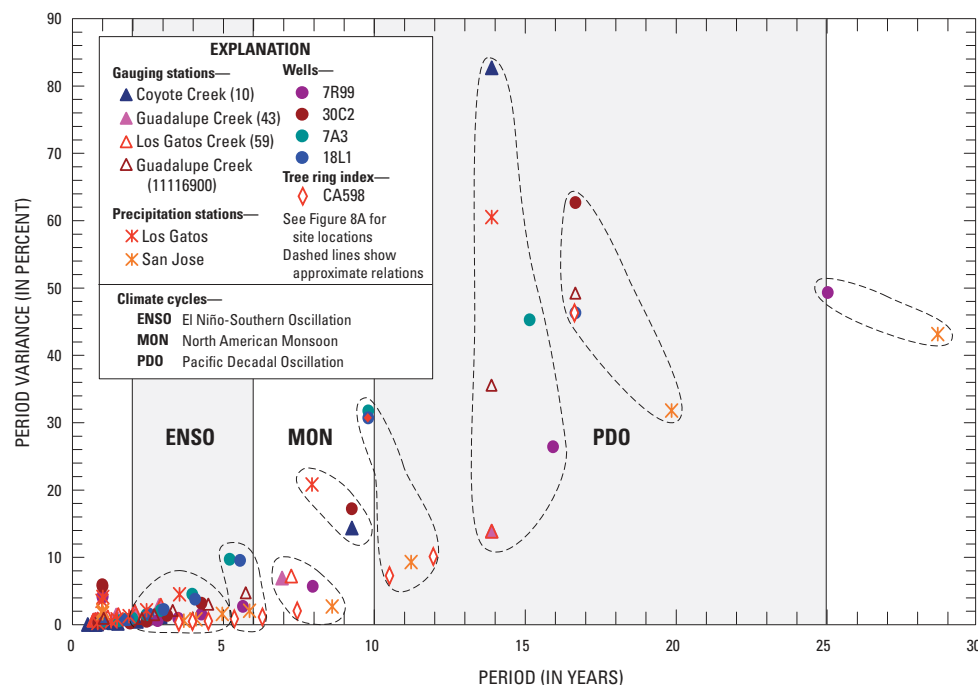


Figure 6. Example of similarities in hydrologic periodicity and percentage of variance in relation to major climate cycles.

water levels, and streamflow are linked directly to the major climate cycles such as PDO and ENSO. The periods of changes in tree-ring indices, precipitation, groundwater levels, and streamflow show a close alignment across all categories of climate cycles (Fig. 6). Groundwater levels from the long-term (1915–2002) index well 7R99 indicate that over 75% of the variation is consistent with PDO-like cycles (Figs. 6 and 7) and lag behind the PDO component of the precipitation by ~21 mo. The variations of the monsoonal and ENSO-like cycles contribute another 12% of the variation in groundwater levels (Fig. 6) and lag behind the precipitation cycles by ~18 and 3 mo, respectively. The overall changes in groundwater levels are largest when these cycles are more closely in phase with the PDO-like cycles, as occurred in the late 1930s and 1970s and the early 1980s (Fig. 7), yet the amplitude of the monsoonal and ENSO components generally is larger

during cool (negative) PDO cycles. The annual variation, which largely reflects urban water-supply demand, shows increases during cool (negative) PDO periods during the mid-1900s prior to the importation of additional surface-water supplies (Fig. 7).

Estimated cycles within streamflow include ENSO-like cycles ranging from 2 to 6 yr, North American monsoon-like cycles ranging from 7 to 9 yr, and PDO-like cycles ranging from 13 to 17 yr (Fig. 6). The larger PDO cycles are missing from these streamflow records owing to the shorter periods of record and the predominantly runoff-based flow measured at these gauging stations. Even with the regulated streamflow along the Los Gatos Creek and the Guadalupe River, these streams also show alignment with the ENSO, North American monsoon, and PDO cycles. These cycles are consistent with the cycles of floods and droughts shown by Freeman (1968) for Southern California and the

major ENSO events and the warm and cool PDO cycles (Fig. 4A). For the 30 yr of record (1970–2000), Los Gatos, Guadalupe, and Coyote Creeks all exhibit the common period of 13.9 yr within the PDO-like cycles (Fig. 6), with Guadalupe River also exhibiting a longer 17 yr cycle for the longer record (1929–2000; Fig. 6). Over 95% of the variation in streamflow for Guadalupe River is in alignment with these three climate cycles (Fig. 6).

The cycles of streamflow also are correlated with periodic changes in precipitation and groundwater levels. The PDO cycle of Guadalupe Creek leads the PDO and ENSO cycles of precipitation by 16 and 2 mo, respectively. The monsoonal cycle of Los Gatos Creek leads the precipitation monsoonal cycle by 27 mo. Changes in groundwater levels exhibit a 34 mo lag, relative to streamflow for PDO cycles, and lead the ENSO cycle of streamflow by 2 mo for Guadalupe Creek.

### Stream-Aquifer Interaction

Streamflow has been affected by development of the aquifer system and regulated flow from reservoirs as well as by conjunctive use of groundwater and surface water. The decrease in groundwater pumpage generally has contributed to additional streamflow, with reduced recharge in upper reaches and greater base flows in the lower reaches (Figs. 8A and 8B). Streamflow, base flow, and storm-related runoff events contribute to gaining reaches of streamflow during exceptionally wet years on Coyote, Los Gatos, and Guadalupe Creeks (Figs. 8A and 8B). The upstream and downstream reaches of Los Gatos Creek commonly exhibit the opposite behavior, with increased streamflow in the upper reaches followed by immediate downstream losses owing to infiltration in the lower reach (Figs. 8A and 8B). However, both reaches showed persistent gains in the late 1980s during the drought (Figs. 8A and 8B). Similarly, Guadalupe Creek shows the opposite behavior between upstream and successive downstream reaches, with more gains in the lower reaches and persistent streamflow gains in the lowest gauged reaches (Figs. 8A and 8B). Streamflow also has been augmented by releases

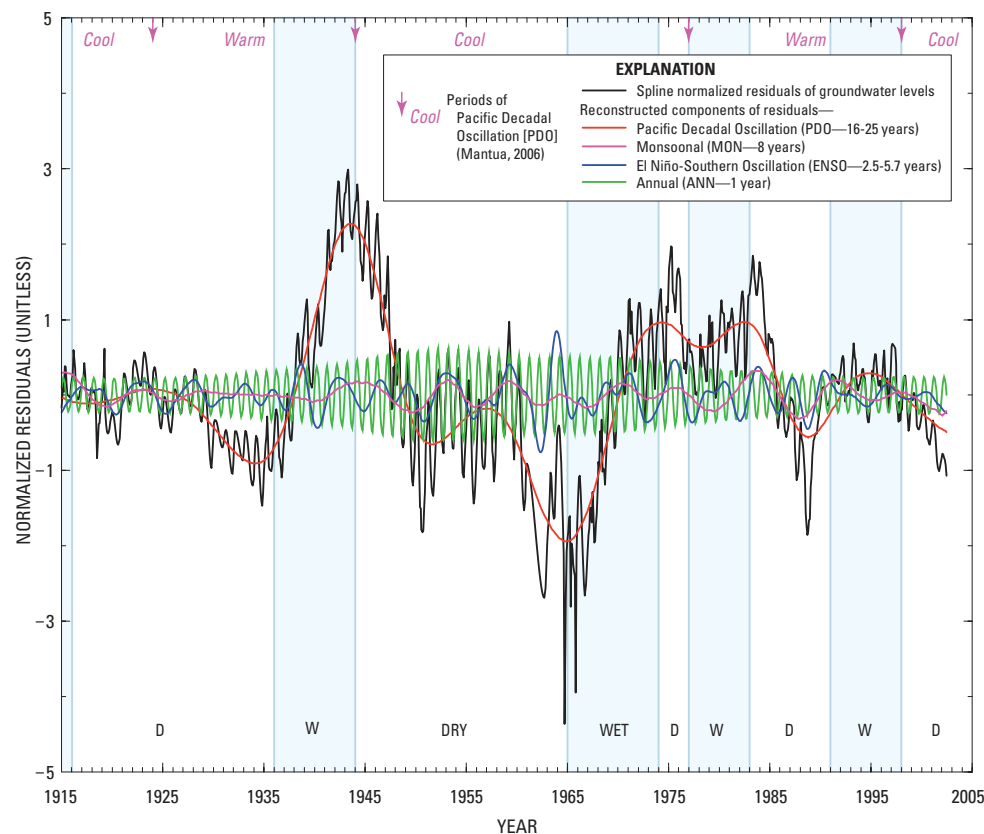


Figure 7. Frequency components of groundwater levels from the long-term index well, Santa Clara Valley, California.

from reservoirs, and from the direct discharge of imported water into Coyote, Saratoga, Stevens, Los Gatos, and Guadalupe Creeks, and the discharge of reclaimed water into Alamitos Creek in the 1980s. Since the recovery of the groundwater levels, ~3% of the streamflow that infiltrates along the west-side streams becomes rejected recharge in the lower reaches of these tributaries, as indicated between the gauges on Los Gatos, Guadalupe, and Coyote Creeks (Figs. 8A and 8B).

Streamflow gains and losses also covary with changes in groundwater levels. For example, the annual cycles of changes in groundwater levels gen-

erally lag behind the changes in gains and losses by 2–6 mo along Los Gatos Creek (Figs. 8A and 8C). Other creeks, such as Guadalupe, San Tomas Aquino, and Ross Creek, also show increases in groundwater levels that lag behind increased gains in streamflow by several months (Figs. 8A and 8C). The magnitude of the water-level changes partly is dependent on the size of the watersheds, with the smaller creeks, such as Ross and San Tomas Aquino Creeks, having smaller changes in gains and losses relative to larger creeks, such as Guadalupe and Los Gatos Creeks (Figs. 8A and 8C). Thus, streamflow infiltration is contributing to changes in groundwater

recharge and related increases in groundwater storage, as indicated by the rise in groundwater levels of wells near these creeks (Figs. 8A and 8C). Analysis of simulated streamflow infiltration indicates that additional streamflow infiltration also may have been accommodated by downward wellbore flow in wells screened over multiple aquifers near these creeks (Hanson et al., 2003a).

## Groundwater Pumpage from Multiple Aquifers

Interaquifer flow through water-supply wells screened across multiple aquifers is an important component to the flow of groundwater in many developed aquifer systems. Wellbore flow in the Santa Clara Valley was examined using flow measurements, hydrochemistry, and numerical simulations. Interaquifer flow was assessed locally using a combination of wellbore flow measurements and depth-dependent water-chemistry sampling at three water-supply wells and depth-specific samples from multiple-well monitoring sites. Interaquifer flow owing to wellbore flow in hundreds of multiple-aquifer supply wells was assessed regionally using a simulation model of regional groundwater flow (Hanson et al., 2004b).

Wellbore flow and depth-dependent chemical and isotopic data indicate that flow into the well from multiple aquifers, as well as capture of artificial recharge by pumping of water-supply wells, predominantly is occurring in the upper 500 ft (152 m) of the aquifer system (Fig. 9). The wellbore flow logs from four wells indicate a consistent pattern, where the upper-aquifer system accounts for 66% at 12th Street No. 10, 82.5% from Williams No. 3, 95% at Mountain View No. 20 of total wellbore inflow, and ~74% of total wellbore inflow at California Water Service (CWS) No. 17 (Figs. 9 and 10). Results of depth-dependent and depth-specific sampling confirm that on the west side of the valley, the groundwater in the shallower aquifers (<500 ft [152 m] depth) contains a substantial amount of water from artificial recharge, as evidenced by the flow and chemistry data from Williams No. 3 (Fig. 9A). Deuterium and oxygen isotopic data indicate that as much as 60% of the water pumped from production



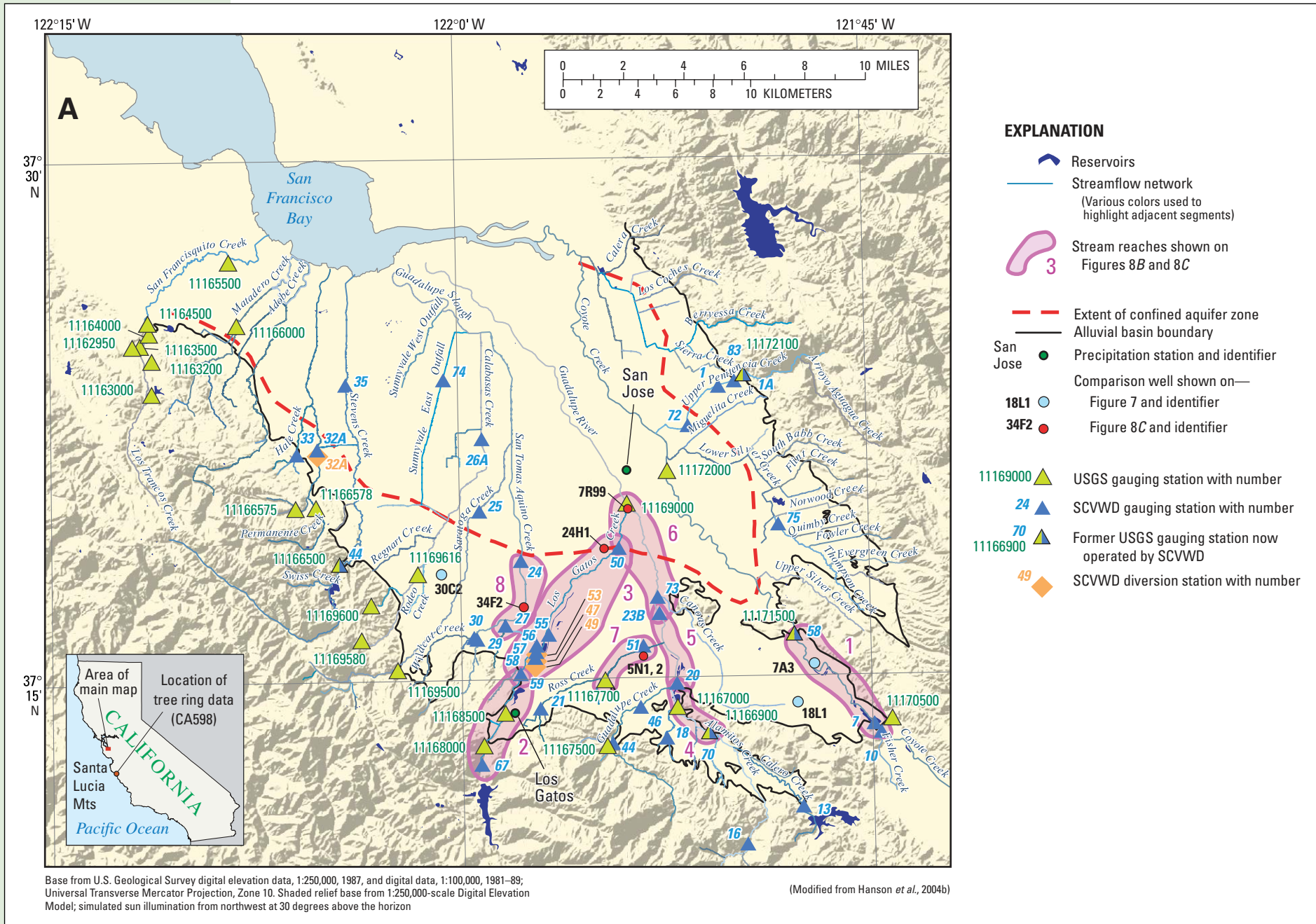


Figure 8. (A) Map showing location of selected streamflow reaches and related gauging stations and wells. USGS—U.S. Geological Survey; SCVWD—Santa Clara Valley Water District. (Continued on following two pages.)

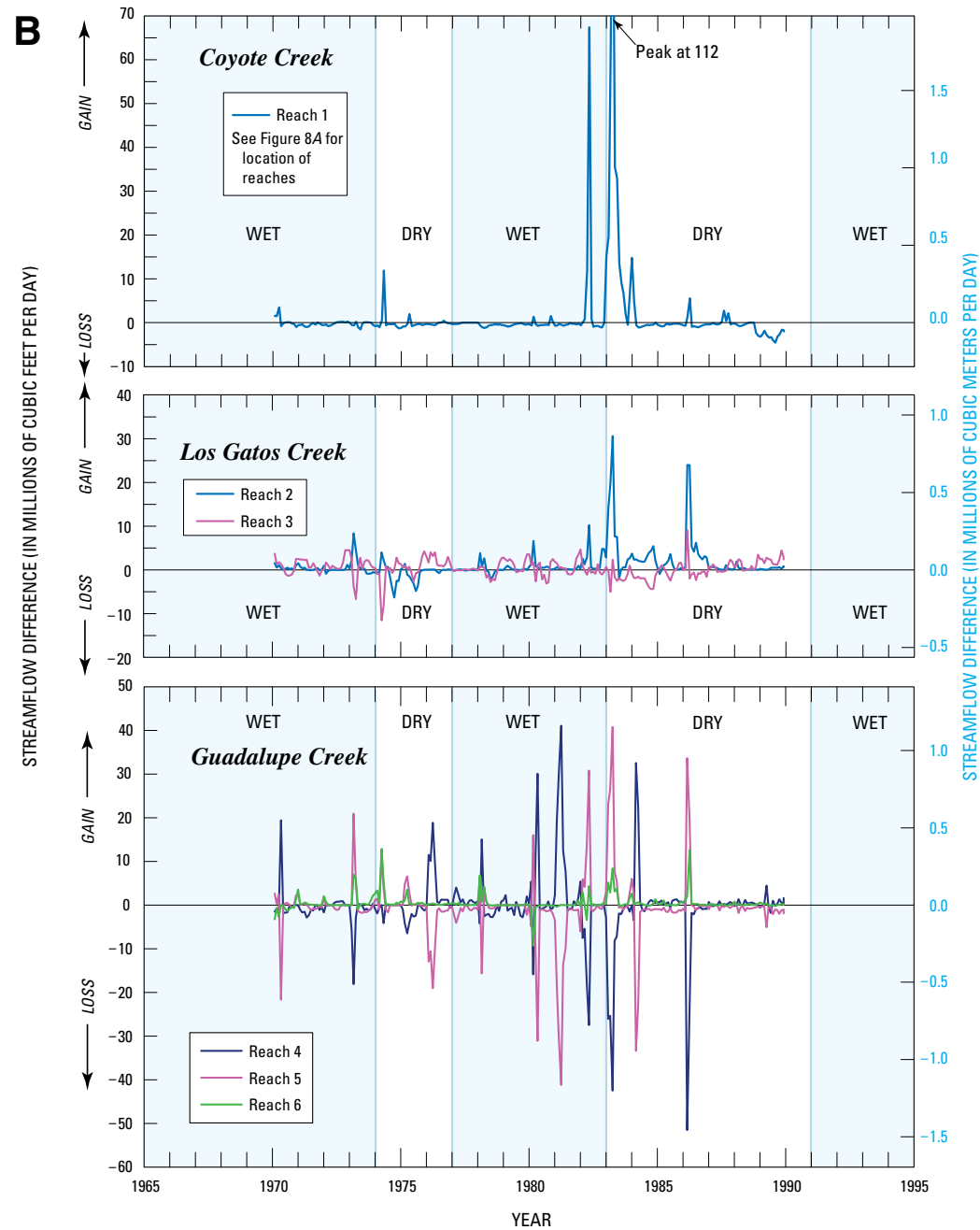


Figure 8 (continued). (B) Graph showing streamflow gains and losses for selected streams.

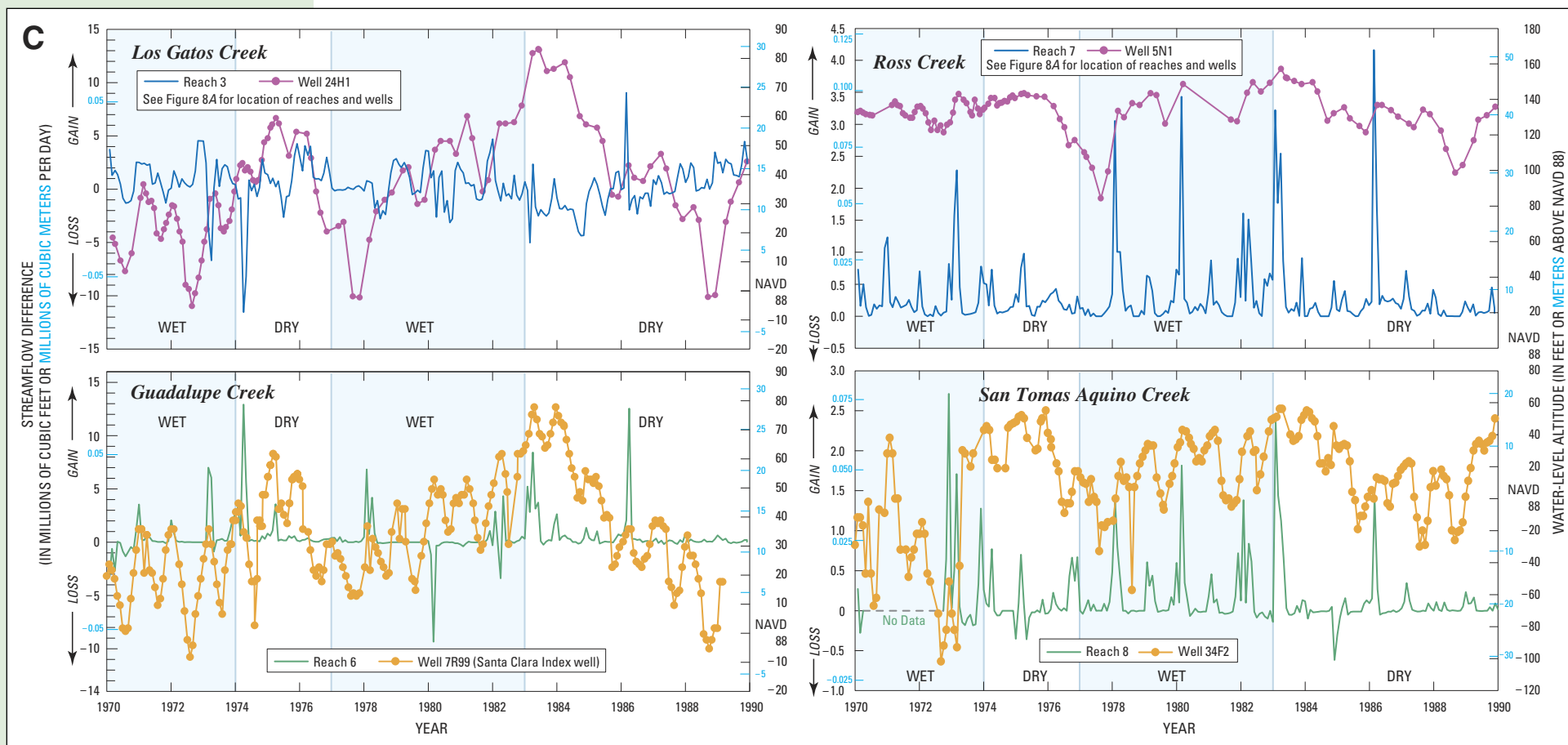


Figure 8 (continued). (C) Graph showing streamflow gains and losses for selected streams and nearby groundwater levels, Santa Clara Valley.

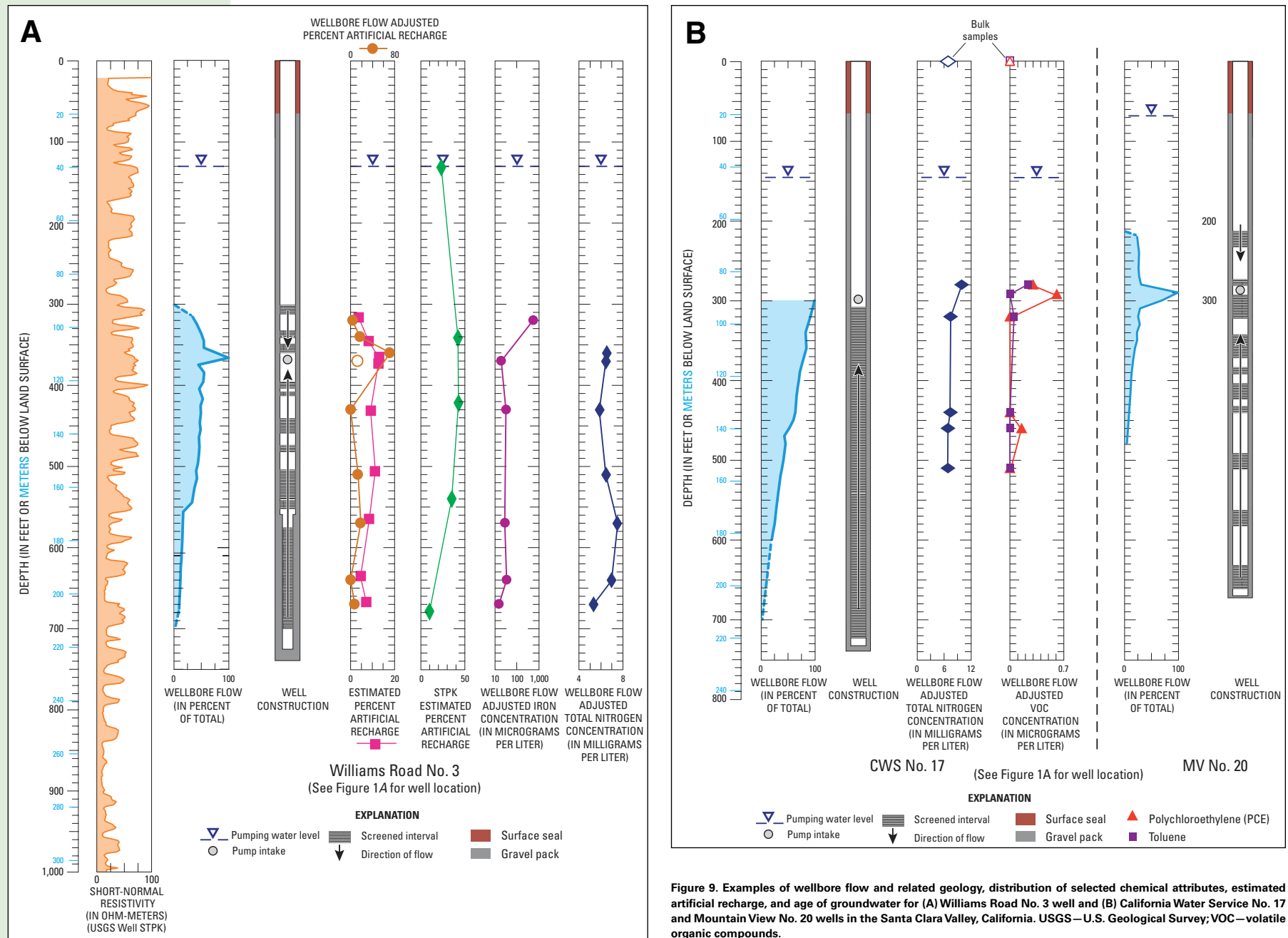
wells in this area originated as artificial recharge (Fig. 1). Thus, the capture of artificial recharge from multiple-aquifer wells is an important part of the water-supply cycle in the Santa Clara Valley.

The effects of wellbore flow within large water-supply well fields is demonstrated by wellbore flow and chemistry data collected from 12th Street No. 10 and the nearby Coyote Creek Outdoor Classroom (CCOC) monitoring-well site (Figs. 1A and 9). In this example, a major percentage (43%) of the pumped water was captured from the uppermost

aquifer layers above the pump intake (Fig. 10). Yet, the tritium, nitrate, and carbon-14 age dates from depth-dependent samples indicate that recent water is circulating to the bottom of this well (Fig. 10). Even though downward hydraulic gradients indicate the potential for downward flow at the nearby CCOC monitoring-well site, these isotopic relations are not present at this nearby monitoring-well site. The absence of these geochemical relations would suggest that groundwater is circulating through wellbores to the lowermost aquifers through un-

pumped wells that are close to actively pumping wells in these clustered well fields (Fig. 10).

The regional effects of wellbore flow were assessed with a regional groundwater flow model that simulated wellbore flow from hundreds of wells screened across multiple aquifers, using the multi-node well package in MODFLOW-2000 (Halford and Hanson, 2002). The simulated, intra-wellbore flow accounts for ~19% of the average net simulated regional groundwater flow and almost all inter-aquifer vertical flow, and it occurs in pumped and



**Figure 9.** Examples of wellbore flow and related geology, distribution of selected chemical attributes, estimated artificial recharge, and age of groundwater for (A) Williams Road No. 3 well and (B) California Water Service No. 17 and Mountain View No. 20 wells in the Santa Clara Valley, California. USGS—U.S. Geological Survey; VOC—volatile organic compounds.



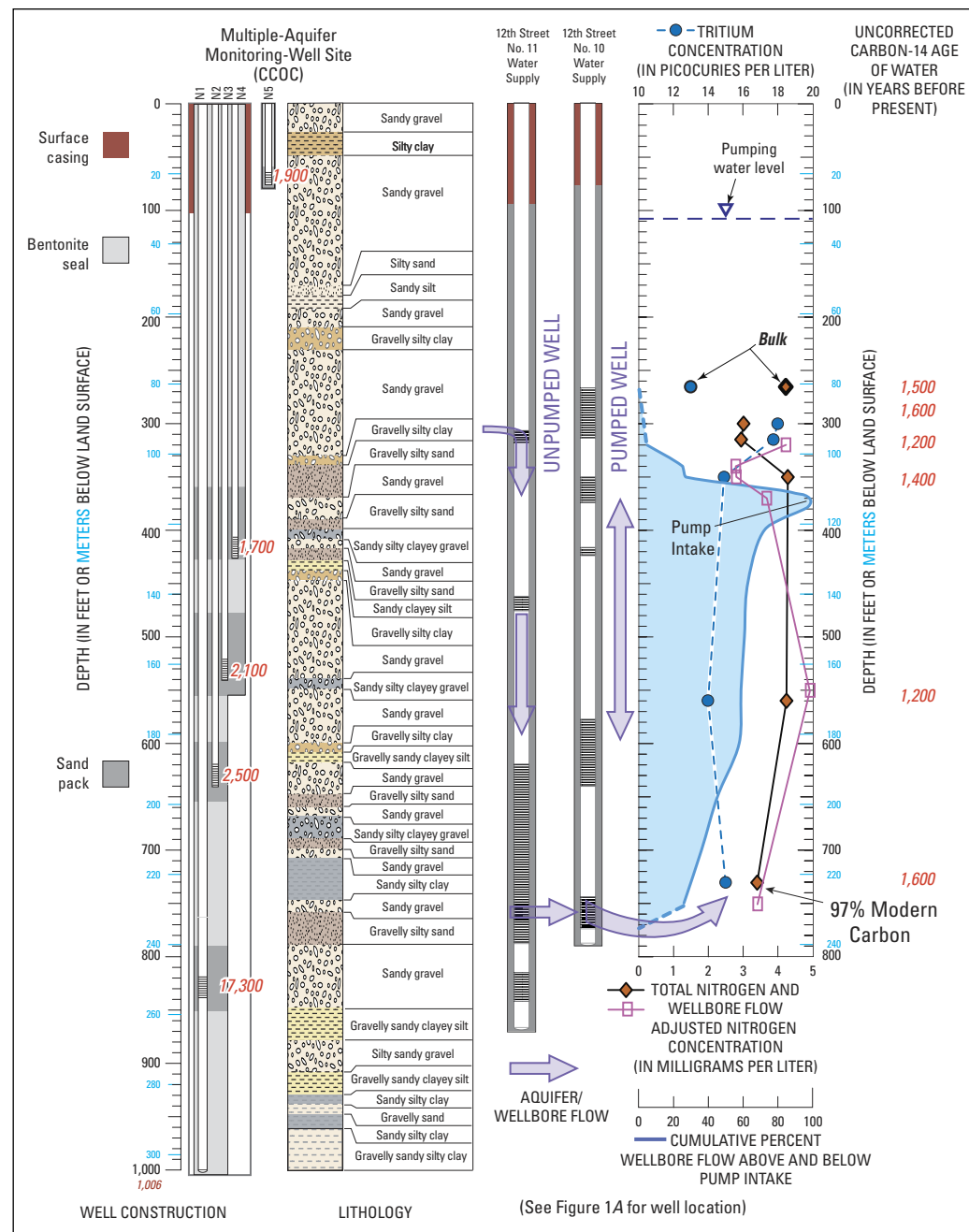


Figure 10. Diagram showing distribution of wellbore flow in the 12th Street No. 10, and relation between adjacent water-supply wells in well field and the CCOC multiple-well monitoring site, Santa Clara Valley, California.

unpumped multiple-aquifer wells (Fig. 3B). Because wellbore flow in wells screened over multiple aquifers is the main component of vertical flow between aquifers, it also is the main conduit for recharge to the lower aquifers where multiple-aquifer wells are present. In addition, simulation results indicate that the presence of wellbore flow can cause increased streamflow infiltration in the upper-aquifer layers and reduced subsidence in the lower-aquifer layers. Thus, wellbore flow enhances deep recharge and, as such, supplies some of the water that otherwise would have been simulated as water from aquifer and aquitard storage depletion in the lower aquifers (Hanson et al., 2003a).

## Subsidence

Historic groundwater overdraft in the Santa Clara Valley caused up to 12.7 ft (3.9 m) of land subsidence from 1916 to 1969 (Poland and Ireland, 1988). Starting in the late 1960s, the SCVWD began importation of new surface-water supplies for direct delivery and artificial recharge. These surface-water deliveries significantly reduced groundwater pumpage, which was driving the historical subsidence and generally put most of the basin in a long-term water-level recovery.

Declines in water levels and increases in vertical gradients between aquifers can contribute to land subsidence. Land subsidence can occur seasonally, over multiyear climatic cycles, or in response to long-term storage depletion from groundwater mining. Differential land subsidence also can provide localized hazards to rail, pipe, and highway alignments and grades. To better understand and manage subsidence, new estimates of physical properties were obtained (Newhouse et al., 2004) that confirm previous estimates (Poland and Ireland, 1988). Understanding the distribution of these estimates, relative to pumpage, as well as the spatial and temporal distribution of subsidence, is critical to management of the water resources and minimizing the effects of land subsidence.

New specific storage values were estimated from consolidation-test data derived from samples of cores from recently completed monitoring-well

sites and from recent extensometer data (Fig. 1). Skeletal elastic specific storage ( $S'_{ske}$ ) values from consolidation tests have a geometric mean of  $1.2 \times 10^{-5} \text{ ft}^{-1}$  ( $0.4 \times 10^{-5} \text{ m}^{-1}$ ), with a range from  $2.7 \times 10^{-6} \text{ ft}^{-1}$  to  $1.4 \times 10^{-4} \text{ ft}^{-1}$  ( $0.8 \times 10^{-6} \text{ m}^{-1}$  to  $0.4 \times 10^{-4} \text{ m}^{-1}$ ). The graphical estimates of  $S'_{ke}$  for data collected from the San Jose and Sunnyvale extensometers for the period 1983–2001 are  $\sim 1.2 \times 10^{-3}$  and  $6.2 \times 10^{-3}$ , respectively. These result in  $S'_{ske}$  values on the order of  $1.5 \times 10^{-6} \text{ ft}^{-1}$  and  $1.5 \times 10^{-5} \text{ ft}^{-1}$  ( $0.5 \times 10^{-6} \text{ m}^{-1}$  and  $0.5 \times 10^{-5} \text{ m}^{-1}$ ) for San Jose and Sunnyvale, respectively, based on the aggregate thickness of fine-grained deposits. The  $S'_{ke}$  and  $S'_{ske}$  estimates for the San Jose extensometer are comparable with the previous estimates of  $1.5 \times 10^{-3}$  for  $S'_{ke}$  and  $1.9 \times 10^{-6} \text{ ft}^{-1}$  ( $0.6 \times 10^{-6} \text{ m}^{-1}$ ) for  $S'_{ske}$  reported for the San Jose extensometer (Poland and Ireland, 1988), and other reported values for alluvial deposits (Ireland et al., 1984; Hanson, 1989). Even though the geometric mean from consolidation tests is greater than the value commonly estimated from reported values, it falls within the range of values derived from graphical estimates of local extensometer data.

The new estimates of elastic and inelastic specific storage values also appear to be related to the distribution of wellbore flow (Fig. 11; Hanson et al., 2005b). The primary zones where groundwater enters the water-supply wells are inferred from the temperature gradient logs from the CCOC and Guadalupe (GUAD) monitoring-well sites and from the wellbore flow logs from the nearby water-supply well (Hanson et al., 2003a; Newhouse et al., 2004). The normal conductive temperature gradients are disturbed from a relatively linear and nearly constant value within zones where predominantly lateral groundwater flow cools the aquifer and causes selective reductions in the natural conductive geothermal gradient. Thus, the numbered regions shown on Figure 11 are zones where lateral groundwater flow is occurring. These zones also are coincident with the sloped parts of the cumulative wellbore flow curves that represent zones of lateral groundwater inflow in water-supply wells. These data suggest that repeated pumping cycles that drive changes in effective stress and related compaction contributed to the preferential reduction of the elastic and inelastic storage properties

of the zones with the greatest contribution to wellbore flow. The estimated inelastic specific storage values coincident with the intervals of well screens are  $\sim 52\%$  (GUAD) to  $76\%$  (CCOC) of the values above and below these intervals of greatest wellbore flow. Similarly, the estimated elastic values were  $\sim 49\%$  (GUAD) to  $88\%$  (CCOC) of the zones of reduced pumpage (Fig. 11; Hanson et al., 2005b).

Land subsidence since the 1980s has been predominantly elastic and occurs over seasonal and climatic cycles (Fig. 12), with extensometer data suggesting that all excess pore pressure is dissipated seasonally (Hanson et al., 2005b). The simulated seasonal elastic compaction was as great as 0.11 ft (0.03 m) at the San Jose extensometer (Fig. 12) in response to seasonal water-level changes of  $\sim 60$  ft ( $\sim 18.3$  m). This seasonal elastic compaction is superimposed upon longer-term simulated, predominantly elastic compaction of  $\sim 0.32$  ft ( $\sim 0.1$  m) from 1983 to 1989 and recovery (uplift) from 1989 to 1990 (Fig. 12). This multiyear trend was driven by water-level declines of as much as 116 ft (35 m) during the drought of the late 1980s. The sustained water-level decline during the dry periods of climate cycles resulted in additional compaction along the outer margins of the historic region of subsidence (Hanson et al., 2004b). Some of this compaction was inelastic and may have occurred during the peak summer months of the drought years when maximum water-level declines of the peak pumping periods exceeded the previous preconsolidation heads. This also may have led to localized and differential subsidence around the large cones of depression, along the margin of the historic region of subsidence, and adjacent to areas of shallow bedrock such as the subcrop of the plunging ridge that extends northwest from Oak Hill (Fig. 1B; Langenheim et al., 2014). Differential subsidence may be most pronounced around the well fields in the valley, as evidenced by large seasonal and climatic water-level declines concentrated in these areas (Hanson et al., 2004b) and localized deformation identified from seasonal and multiyear InSAR imagery (Galloway et al., 2000). Compaction data from the nested extensometers at the Sunnyvale site indicate that most of the compaction occurred below the upper extensometer

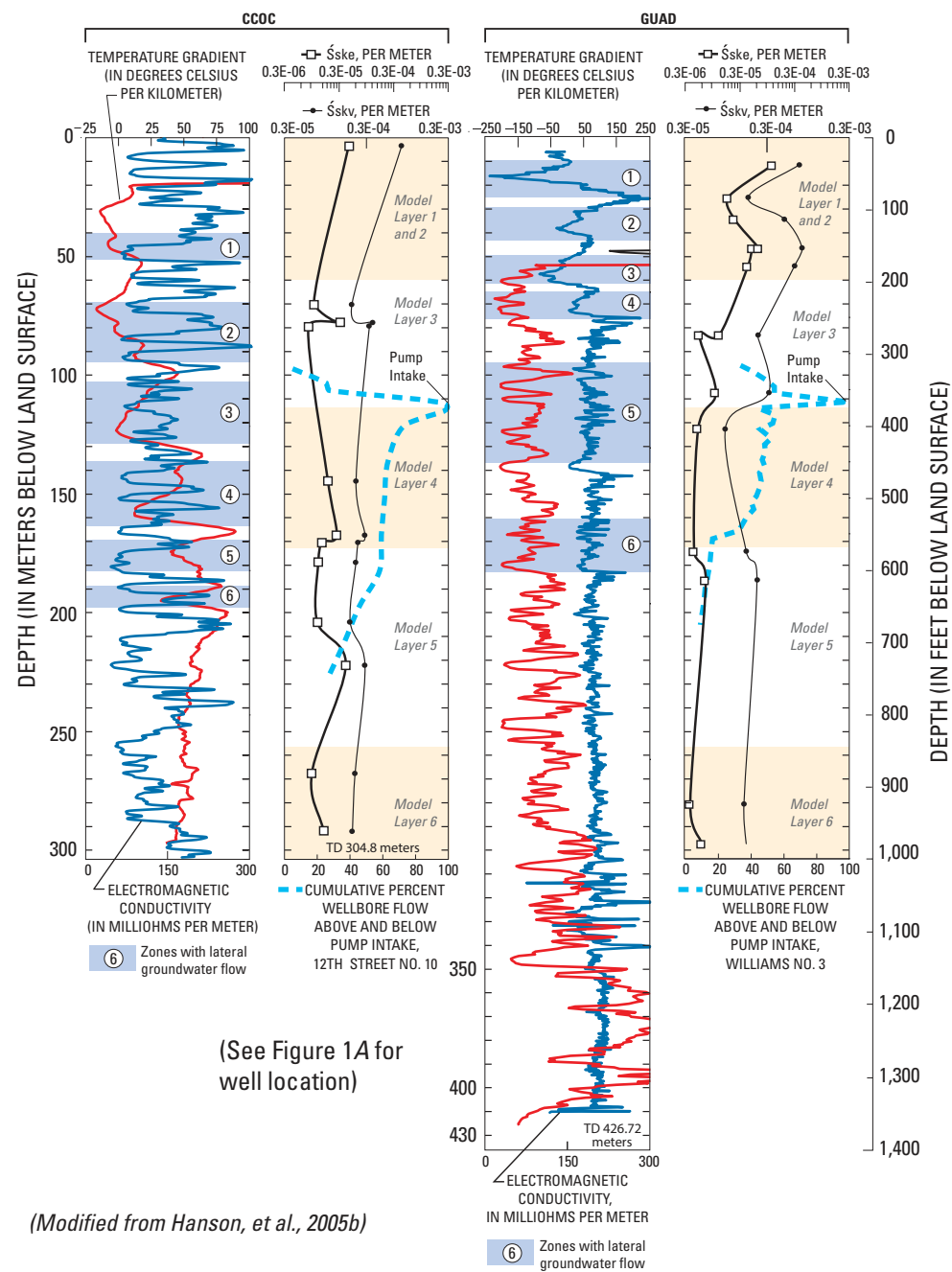


Figure 11. Graph showing the distribution of elastic and inelastic specific storage, and thermal gradient data for CCOC and GUAD monitoring wells and wellbore flow from 12th Street No. 10 and Williams No. 3, Santa Clara Valley, California.

(>250 ft [>76 m] below land surface; Fig. 12). This is consistent with the typical range of well completions, wellbore flow measurements from supply wells, and thermal-gradient data from monitoring-well sites, which collectively indicate that most pumpage occurs within the upper-aquifer system between 300 and 650 ft (91 and 198 m) below land surface (Figs. 11 and 12).

### Artificial Recharge

Artificial recharge represents about one-half of the inflow of water into the valley. Imported water and local runoff are infiltrated through 400 acres (1.62 km<sup>2</sup>) of ponds and by direct release on selected streams. The relative mixtures of imported water can be assessed from the analysis of major ions and isotopes. For example, the yellow shaded region in Figure 13 represents the imported water used, in part, for artificial recharge, on the basis of major-ion diagrams (Piper, 1944). The samples of the imported water from the Central Valley Project precede and span the 1976–1977 drought (Newhouse et al., 2004). The imported water spans a wide range of major-ion chemistry, from wet years (1974) when the water is similar to local runoff in dry years (1976–1977; Fig. 13). Even though the imported water is of relatively good quality, it trends toward more salinity during the 1976–1977 drought. This may reflect increased salinity derived from the imported water passing through the Sacramento River delta on its way to Santa Clara Valley (Fig. 13).

The percentage of artificial recharge was estimated from monitoring-well and water-supply-well samples assuming a binary mixture, following the method from Muir and Coplen (1981), and using the isotopic deuterium values for local and imported-water recharge (Hanson et al., 2002; Newhouse et al., 2004). The percentage of artificial recharge ranges from 0% to 61% for water-supply wells. Supply wells with water containing more than 15% artificial recharge typically are down gradient and in close proximity to the artificial recharge ponds (Fig. 1A). Similarly, samples from monitoring wells range from almost no artificial recharge (0 percent [MGCY-3] and 2% [CCOC-4]) at depth to as much

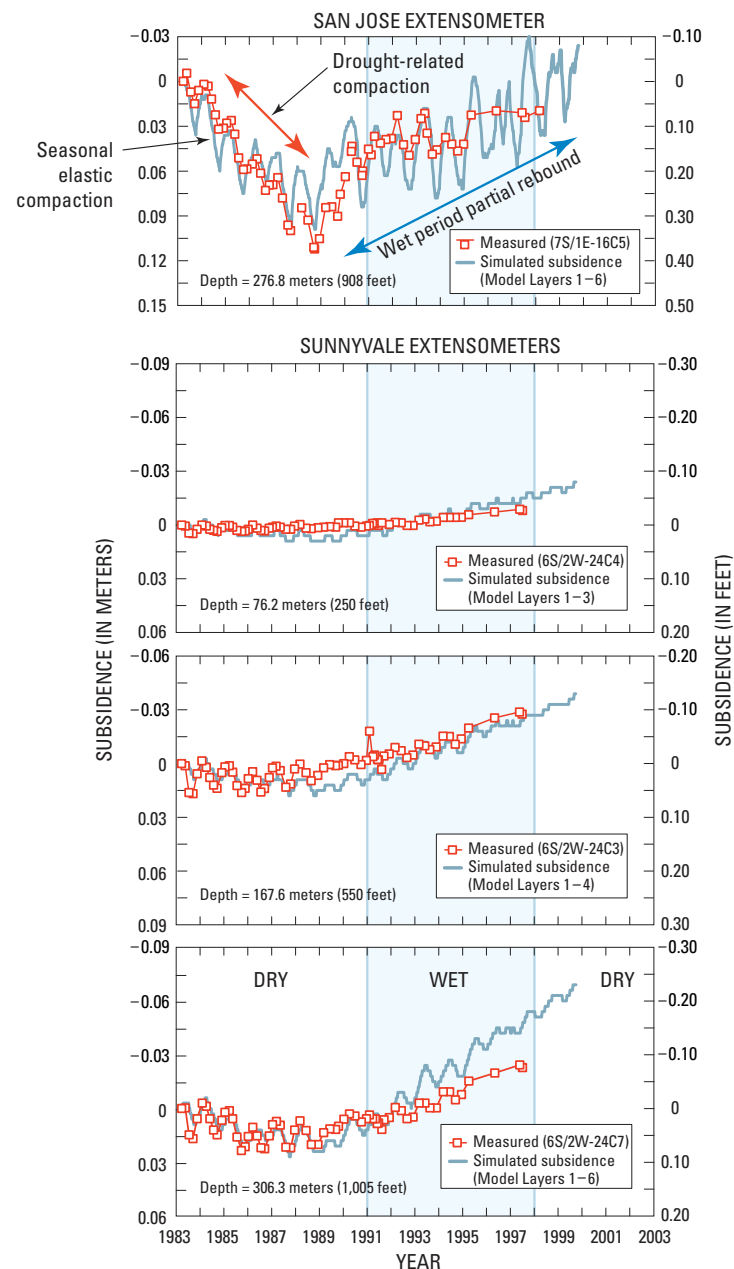


Figure 12. Graph showing measured and simulated subsidence for the extensometers at San Jose and Sunnyvale in the Santa Clara Valley, California.



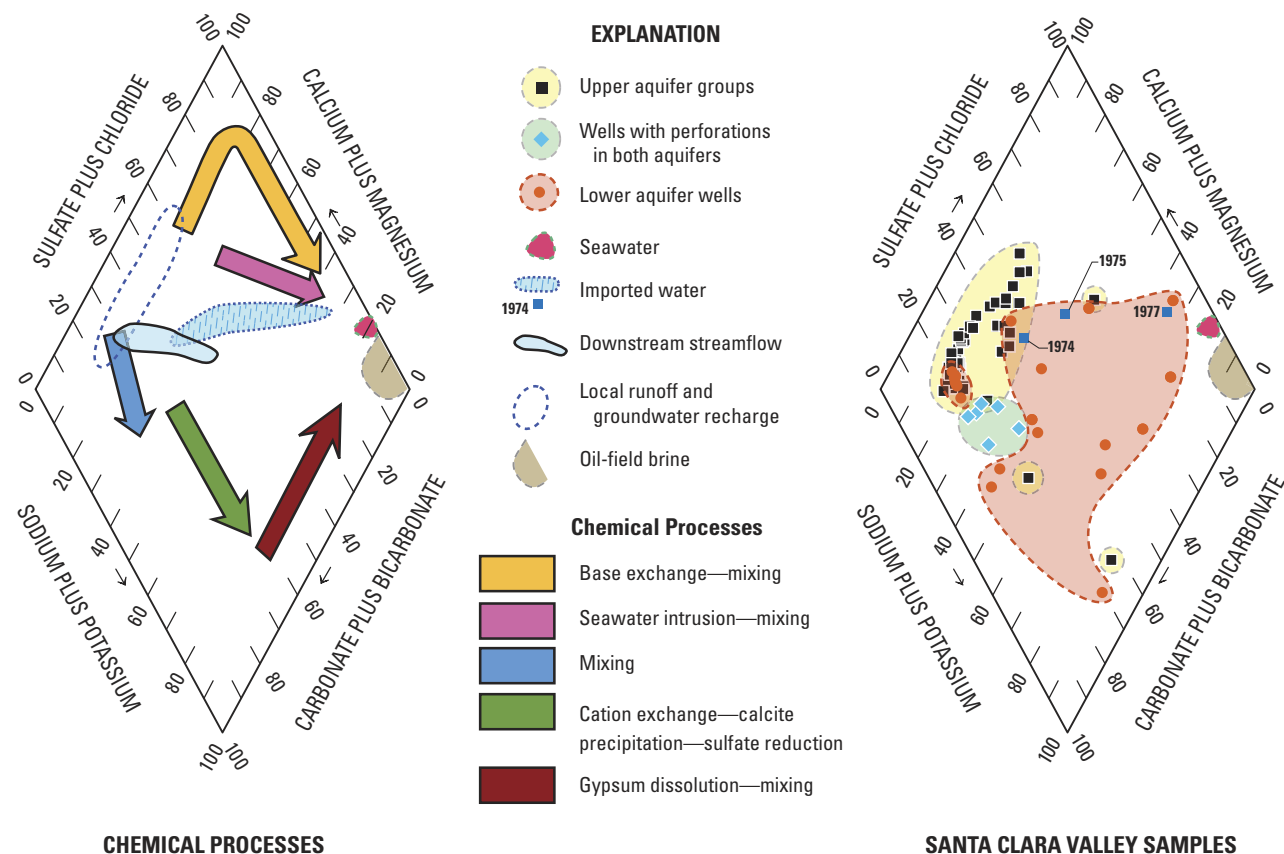


Figure 13. Piper diagrams showing types of chemical processes typical of coastal aquifers and water types related to natural and artificial recharge from the Santa Clara Valley, California.

as 70% (MGCY-5) of imported-recharge water in shallow monitoring wells that are directly beneath the recharge ponds adjacent to Los Gatos Creek (Newhouse *et al.*, 2004), supplied with local and imported water. The distribution of isotopic values from depth-specific samples indicates that the monitoring wells located along the western margin tend to contain more artificial recharge than the wells located in the center of the valley, which contain less artificial recharge and generally are closer to the isotopic composition of local streamflow

(Fig. 14A). Composite and depth-dependent samples from water-supply wells show similar distributions of isotopes, indicative of mixtures of artificial recharge of imported water and natural recharge from local streamflow, with larger percentages of artificial recharge in water-supply wells near artificial-recharge sites on the western side of the valley (Fig. 14B). On the basis of the stable isotope binary mixtures (Hanson *et al.*, 2002) of local recharge and imported-water recharge (Muir and Coplen, 1981), the estimated percentage of artificially recharged

and imported water detected in water-supply wells extends to as much as 40% artificial recharge (Newhouse *et al.*, 2004). Proportions of artificial recharge from monitoring wells, such as STPK (40%), also are similar to flow-adjusted mixtures in depth-dependent samples from comparable depths in nearby water-supply wells such as Williams No. 3 (70%; Fig. 9). Artificial recharge is an important part of the hydrologic cycle in the developed flow system. These estimates indicate that artificial recharge is being stored in the aquifers and moving through

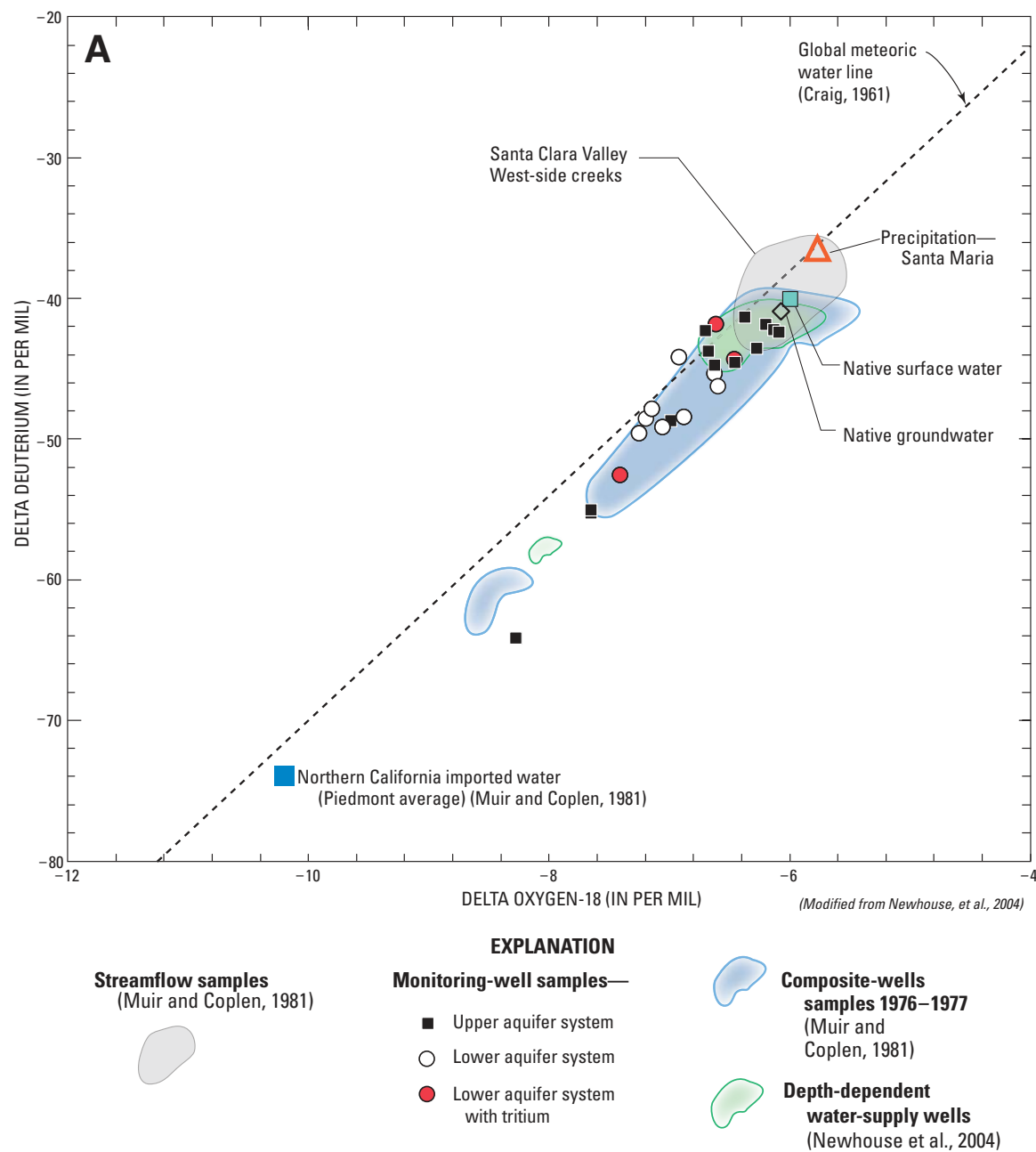


Figure 14. (A) Graph showing stable isotope composition of water from monitoring-well sites in the Santa Clara Valley, California. (Continued on following page.)

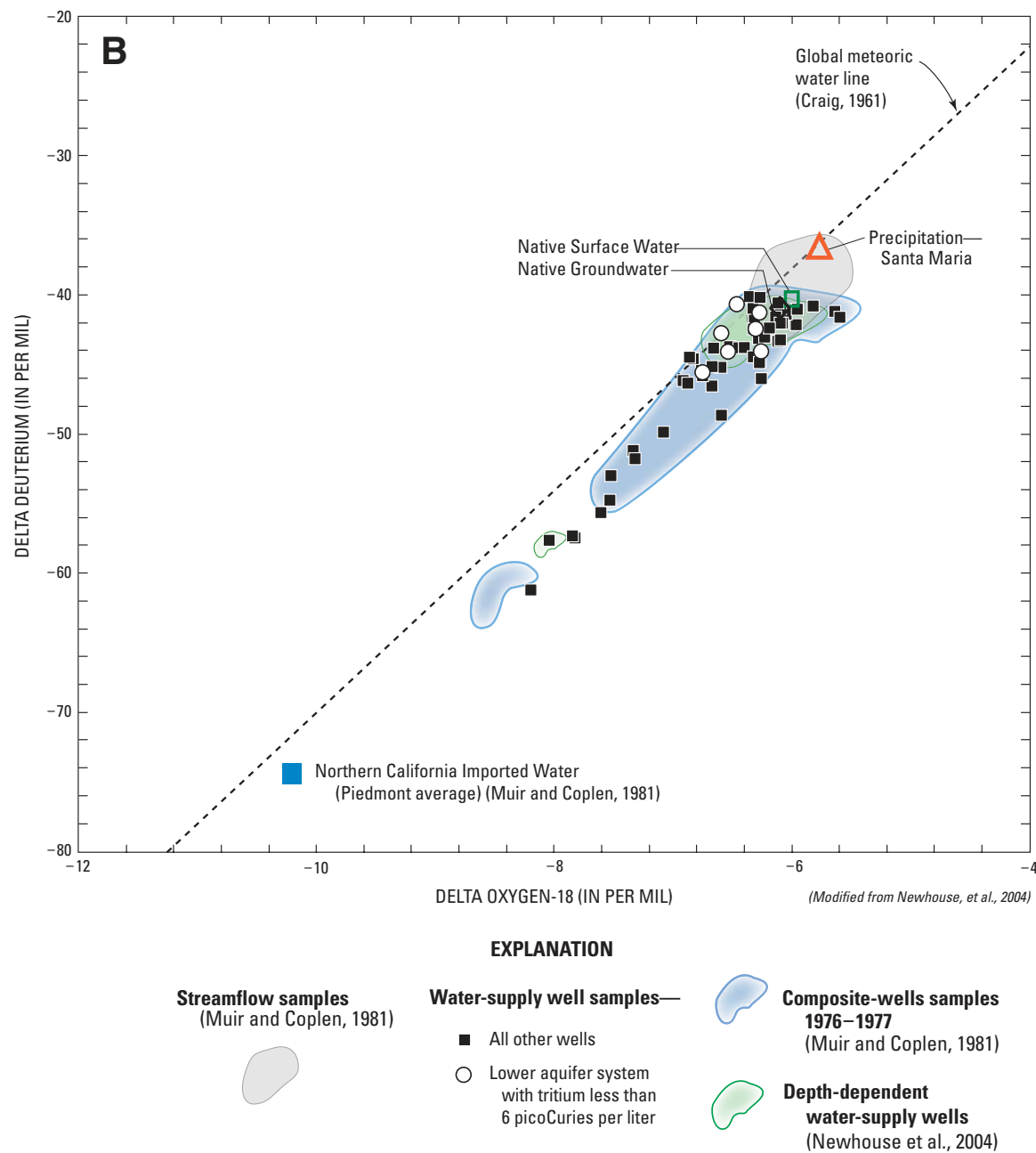


Figure 14 (continued). (B) Graph showing stable isotope composition of water from water-supply wells in the Santa Clara Valley, California.

the upper parts of the flow system. It is captured by pumping the water-supply wells for use during periods of demand, or it becomes wellbore flow and recharges the lower aquifers during periods when the wells are not pumped during reduced demand.

## ■ GEOCHEMISTRY

Managing and sustaining the quality of the water in the Santa Clara Valley require understanding of the geochemistry of local groundwater and surface water and of the imported water used to replenish these resources. The changes in the groundwater flow system, as described in the previous sections, also have affected the water quality through changes in water chemistry. In this section, we briefly discuss general water quality, differences between shallow and deeper aquifer systems, geochemical transformations, seawater intrusion, and other potential sources of salinity.

### Overall Water Quality

Overall, the natural quality of most groundwater in the Santa Clara Valley is good and is low in total dissolved solids and chloride (Newhouse et al., 2004). However, selected minor elements, including iron, manganese, fluoride, boron, and bromide, may locally affect the water quality. These constituents, which are largely naturally occurring, potentially may pose some limitations on the use of water from some wells or necessitate additional well maintenance. In addition, these constituents, with localized occurrences of elevated nitrate concentrations, may come close to occasionally exceeding the U.S. Environmental Protection Agency (USEPA) maximum contaminant levels (MCL) and secondary MCLs (SMCLs; U.S. Environmental Protection Agency, 1994). Similarly, groundwater from some wells contains trace amounts of volatile organic compounds (VOCs), which are well below the drinking-water limits but represent anthropogenic tracers. In the Los Gatos Creek area, samples from some wells and cores from monitoring-well sites contain trace amounts of chromium, nickel, and mercury, which also are well below the drinking-water limits.

The percentages of major ions demonstrate the groupings, as well as the source, evolution, and movement of groundwater, relative to natural recharge from streamflow in the Santa Clara Valley. Major-ion diagrams (Piper, 1944) indicate that the groundwater from wells having similar major-ion chemistry can be grouped into upper- and lower-aquifer system groups (Fig. 14). The spread of values also suggests that mixing and other chemical reactions are occurring along flow paths indicated in the processes diagram (Fig. 14). In Figure 13, the ion chemistry of water samples from the multiple-well monitoring sites, depth-dependent water-supply well samples, and composite water-supply well samples are compared with three potential surface-water end members, seawater, and oil-field brines. The blue shaded region (Fig. 13) represents the major-ion composition of streamflow from Permanente and Saratoga Creeks on the west side of the valley (Myhre and Bencala, 1998). This region partially overlaps the yellow imported-water region because the composition of streamflow on Saratoga Creek includes a mixture of imported-water artificial recharge and local streamflow (Myhre and Bencala, 1998). The samples from shallower monitoring wells group with streamflow from the western side of the valley, as shown by the blue shaded area in Figure 13.

Most of the deeper monitoring and water-supply wells from the central part of the valley appear to have different major-ion chemistry and may represent different water from the deeper aquifers that does not receive recent streamflow or artificial recharge (Fig. 13). In particular, some of the samples from the Eleanor Park (ELNR) site in Palo Alto are more saline and may represent very different waters, relative to the other deep monitoring wells. These waters are trending toward the composition of seawater and may represent a diluted older seawater. Even though Miocene-aged oil deposits related to the Monterey Formation were pumped briefly in the Cupertino area and oil shows were reported in several water-supply wells, no samples appear to resemble typical oil-field brines (Fig. 13).

Most supply wells appear to group with the monitoring wells and with the west-side streamflow samples (Fig. 13). Depth-dependent data

show that the deeper samples in the same supply wells show only a slight trend toward mixing with the deeper monitoring-well compositions (Fig. 13). The majority of these samples are similar in composition to the west-side streamflow samples, which may suggest that downward wellbore flow is occurring in these water-supply wells.

### Differences between Shallow and Deeper Aquifer Systems

On the basis of geochemical data, the source, age, and movement of waters in coastal aquifers generally can be subdivided into shallow and deeper aquifer systems. Shallow aquifers receive the majority of recent recharge, including artificial recharge, while deeper aquifers generally contain older waters and do not receive significant amounts of recent recharge. Isotopic data indicate that artificial recharge is occurring throughout the shallower parts of the upper-aquifer system and that recent recharge (less than 60 yr old) occurs throughout most of the basin but may not be present toward the center of the basin at GUAD below the extensive fine-grained confining units. There is a wide range of groundwater ages. Uncorrected carbon-14 data indicate that the groundwater in the upper 500 ft (152 m) generally is less than 2000 yr old, and groundwater in the deeper aquifer layers generally ranges from 16,700 to 39,900 yr old. In addition, many of the wells in the center of the basin with deeper screens do not contain tritium. This would suggest that the water pumped from these wells does not contain recent recharge (less than 50 yr B.P.).

Shallow aquifers often are more susceptible to anthropogenic and natural contamination, as evidenced by trace occurrences of iron, nitrate, and VOCs in selected water-supply wells (Fig. 9). Iron is of particular concern because it regularly fouls well screens in water-supply wells in the Santa Clara Valley, and this reduces the productivity of the affected wells. Wellbore flow-adjusted iron concentrations of depth-dependent samples were largest in the uppermost screens of Williams No. 3 and vary with depth in the lower aquifers (Fig. 9).

Nitrates have been identified in some areas of the valley as a potential issue. Recent nitrate anal-

yses ranged from 0.03 mg/L to 9.3 mg/L as nitrogen in wells and as high as 25 mg/L as nitrogen in pore waters from shallow cores (Newhouse et al., 2004). In the Mountain View area, nitrates in some water-supply wells occasionally approach the drinking water standard; the source of the nitrates was uncertain. Nitrogen isotopes and pharmaceuticals were used to assess the potential source of these elevated nitrate concentrations. Water from several wells in the Mountain View area (MV-No. 20 and CWS-No. 17) had nitrate concentrations of ~5.5 and 7.3 mg/L as nitrogen, respectively (Newhouse et al., 2004). The nitrogen isotopes ranged from 5.7‰ to 6.3‰ for depth-dependent samples taken at MV-No. 20 and ranged from 5.7‰ to 6.8‰ at well CWS-No. 17. The depth-dependent samples of wellbore flow-adjusted nitrate concentrations from CWS-No. 17 indicate that the largest concentrations occur in the uppermost aquifers screened, while concentrations at 12th St No. 10 and Williams No. 3 indicate that the largest concentrations occur at depths between 500 and 650 ft (152 to 198 m) below land surface (Figs. 9 and 10). Whether the nitrates originate from animal or agricultural sources remains inconclusive on the basis of nitrogen isotopes alone. However, the absence of pharmaceuticals in the samples from Mountain View (MV) No. 20 and CWS-No. 17 suggests that the nitrates in the Mountain View area may not be related to sources from animals but may be residuals from past agricultural activities. Thus, the sources and depth distribution of nitrates may vary across the valley.

Recent sampling for VOCs along three flow paths indicates different patterns and sources of trace amounts of VOC in the aquifers (Fig. 1A). These trace amounts are well below drinking water standards and are primarily anthropogenic tracers that show the depth of penetration of water in the groundwater flow system that has been affected by human activities at the land surface. Samples of groundwater along the Los Gatos flow path (Fig. 1A) contain trace amounts of VOCs associated with solvents and related industrial chemicals. The occurrence of VOCs diminishes down the Los Gatos flow path away from the artificial recharge facilities (Barbara Dawson, USGS, 2005, written commun.).

The trace occurrences of VOCs along the Stevens Creek flow path (Fig. 1A) are different than the other two flow paths. The trace occurrences of VOCs are associated with gasoline components (e.g., toluene) and dry cleaning components (e.g., perchloroethylene [PCE]), and the occurrences diminish down the flow path away from the artificial recharge sites (Barbara Dawson, USGS, 2005, written commun.). Some trace amounts of VOCs were found beneath the confining layers, which suggests that wellbore flow may have facilitated their migration to the deeper aquifers in the confined regions. The distribution is exemplified by the trace concentrations of toluene and PCE from depth-dependent samples at CWS-No. 17. These data are coincident with the movement of the artificial recharge and show that the trace concentrations are greatest within the upper aquifers (Fig. 9). Samples along the Coyote Creek flow path showed lower occurrences of trace amounts of VOCs (Fig. 1A). This may be related to the dilution of flow paths in the convergent flow system, dilution from older VOC-free waters, and the reduced recharge from the Coyote Creek recharge facilities (Barbara Dawson, USGS, 2005, written commun.). These data again reaffirm that the groundwater in the shallower aquifers can be considered more of a renewable resource, with indicators of recent recharge, than those in the deeper aquifers, where no indicators of recent recharge occur. These data also suggest that recent recharge can move and mix with existing groundwater through wellbore flow along the groundwater flow paths from the main recharge areas along the western side of the valley down into the confined parts of the aquifer systems (Fig. 1A).

Multiple-aquifer wells have affected the geochemical character of groundwater in the developed basins by facilitating vertical mixing through wellbore flow of chemically different waters in the shallow and deep aquifers. Abandoned, failed, and unused wells also can provide additional conduits for vertical flow as the aquifers are developed further. Although this may be cause for concern from an aquifer vulnerability perspective, many of these unused wells also may be providing a significant contribution of recharge to the deeper aquifers. This especially may be true in areas where wa-

ter-supply wells have been clustered into well fields. As such, these sources of water can potentially provide additional sources of water to help reduce potential subsidence in lower-aquifer systems or to accommodate additional streamflow infiltration during periods of smaller streamflows (Hanson et al., 2003a).

## Geochemical Transformations

The typical processes of chemical evolution of groundwater in coastal aquifers include cation exchange, carbonate precipitation, sulfate reduction, silicate weathering, clay precipitation, base exchange, and mixing. These chemical transformations are illustrated in a Piper diagram (Fig. 13), where the paths for these chemical transformations are represented by the diamond symbol on the right. The major-ion chemistry of samples from the Santa Clara Valley is shown to the left to exemplify how the major-ion chemistry of waters from the upper- and lower-aquifer systems compare to imported water and local runoff (Fig. 13). Shallow groundwater is chemically similar to the west-side streamflow and, to a lesser degree, the imported water. The imported water varies widely in chemical nature, ranging from water similar to west-side streamflow to water that is more saline in drought years, such as 1977. The groundwater from depth-specific monitoring-well samples as well as depth-dependent and composite samples from water-supply wells shows a progressive evolution that includes cation exchange, carbonate precipitation, and sulfate reduction as water flows from the edges to the center of the basin. Additional chemical changes between shallow and deep samples not only represent different stages of these processes along flow paths at different depths, but also can be attributed to mixing from wellbore flow in the water-supply well samples (Fig. 13). Selected minor and trace elements also vary with depth and location in the valley. Depth-dependent variations in concentrations of lithium, boron, barium, fluoride, strontium, and iron may reflect the changes in sedimentary mineralogy and chemistry of the aquifers.



In addition to changes in ionic chemistry, the chemistry of groundwater can undergo additional changes, which are reflected in isotopic data. Most of the groundwater samples represent water that is isotopically similar (Fig. 14) to water from precipitation and local streams (Hanson et al., 2002; Newhouse et al., 2004). Additional groundwater samples represent an isotopic mixture of native groundwater and imported water (Fig. 14). However, the stable isotopes of oxygen and hydrogen not only represent mixing between colder imported water from the Central Valley, but they also represent older waters recharged prior to the Holocene from the last ice age (Hanson et al., 2002). For this reason, carbon age dates and tritium samples, in conjunction with stable isotopes, are needed to determine which samples are representative of mixtures of recent recharge as opposed to older groundwater that reflects a period of colder climate relative to glacial cycles. The monitoring wells, such as CCOC-1, that are completed in the lower-aquifer system reflect this relation, with little to no tritium, carbon-age dates greater than 10,000 yr B.P., and light stable isotopes (more negative; Fig. 14A; Hanson et al., 2002).

Boron isotopes are another naturally occurring isotope that was used to help identify the potential sources of water. Boron isotopes from monitoring and supply wells indicate a clear partition between the shallow waters that are related to artificial recharge and the older water from the lower-aquifer system (Fig. 15A). The boron isotopic signature from the ELNR monitoring wells (Fig. 1) is heavier than seawater (Fig. 15A), which is typical of adsorption of lighter boron from seawater over long periods of time. This groundwater is analogous to the old seawater sampled in aquifers of Monterey Bay (Hanson, 2003). The boron isotope signature and the ages of this groundwater (greater than 31,000 yr B.P.; Newhouse et al., 2004) from the ELNR wells in Palo Alto indicate these waters may represent older diluted seawater that was never flushed out of the deeper aquifers along the southwestern margin of the San Francisco Bay.

Strontium-87/86 isotopes are naturally occurring stable isotopes of strontium and are expressed as a ratio (Faure and Powell, 1972), which

is used primarily to determine the source of sediments through which the groundwater flows. This is possible because strontium in groundwater undergoes cation exchange between calcium and strontium in the surrounding sediments. This exchange process is relatively rapid for most groundwater flow rates and results in a strontium isotopic composition of groundwater that reflects the isotopic composition of the aquifer sediments. The strontium isotopic signature of water samples from selected monitoring and supply wells (Fig. 15B) shows a partitioning that is different from the boron isotopes. The samples show a geographic partition into two groups that appear to represent wells on the west side and wells from the central part of the valley (Fig. 15B). The gravels encountered in the Pleistocene- and Holocene-aged sediments predominantly are metamorphosed graywacke and metavolcanic rocks; the sands predominantly are metamorphic rock fragments, some of which contain distinctive blueschist-facies minerals and heavy minerals that are typically composed of blue and green amphiboles and chromite (Andersen et al., 2005). The graywackes are common to both the Franciscan Formation and the Great Valley Group, and the abundance of greenstone in the sediments suggests a southern and western source of sedimentation with little sedimentation from the east (Andersen et al., 2005; Marks et al., 2005). Therefore, the grouping of strontium isotopes from water samples (Fig. 15B) is consistent with the interpretation of the source and distribution of sedimentation from analysis of lithic clasts (Andersen et al., 2005).

Serpentinous bedrock and related overlying sediments are present in parts of the lower aquifer system along the west side of the valley in the Oak Hill/Los Gatos region (Oze et al., 2003; Newhouse et al., 2004). Although measured aqueous chromium concentrations are low ( $<4.6 \mu\text{g/L}$ ) in the groundwater samples (Newhouse et al., 2004), the aquifer material warrants study to ensure that the serpentinous bedrock and sediments of the deeper aquifers are not potential natural sources of chromium in the water supply pumped from the lower-aquifer system. Analysis of samples from the WLLO monitoring site indicate that

there were two episodes of deposition of serpentinous sediments that are enriched in chromium, and related trace metals, manganese and nickel. These sediments occur at depths of  $\sim 745$  and  $784$  ft ( $\sim 227$  and  $239$  m) below land surface (Oze et al., 2003) and probably represent early sedimentation in the valley when the plunging bedrock ridge extending northwestward from Oak Hill still was exposed and subject to erosion (Andersen et al., 2005). Although there is no indication of chromium-6 (Cr-VI) contamination from ongoing monitoring, elevated chromium concentrations in the serpentinous sediment, chrome-bearing mineral textures, the estimated reduction-oxidation environment, and water chemistry indicate that the formation of Cr-VI is a possibility for selected water-bearing sediments in the lower aquifers in this region (Oze et al., 2003). Water-mineral interactions were observed from electron microprobe images and the analyses of rock and sediment samples. Combined with water samples from the WLLO site, these data suggest that reinjecting oxygenated water into these deeper aquifers composed of serpentinous sediments potentially could promote chromium oxidation in sediment known to have increased concentrations of chromium (Oze et al., 2003). Many of the deeper groundwater samples indicate reduced waters or waters with relatively low oxygen content ( $<1 \text{ mg/L}$ ), and shallower samples—especially those influenced by artificial recharge—contain relatively larger ( $1\text{--}7 \text{ mg/L}$ ) concentrations of dissolved oxygen (Newhouse et al., 2004). Thus, additional oxidation also could be promoted through downward well bore flow of oxygenated groundwater recharge water through multiple-aquifer wells that are completed and screened into these deeper water-bearing sediments in the Oak Hill–Los Gatos region.

### Seawater Intrusion and Other Sources of Chloride

While some seawater intrusion was identified early in the development of the groundwater resources (Tolman and Poland, 1940), there is no evidence for recent seawater intrusion. However, the seasonal changes in groundwater levels in many

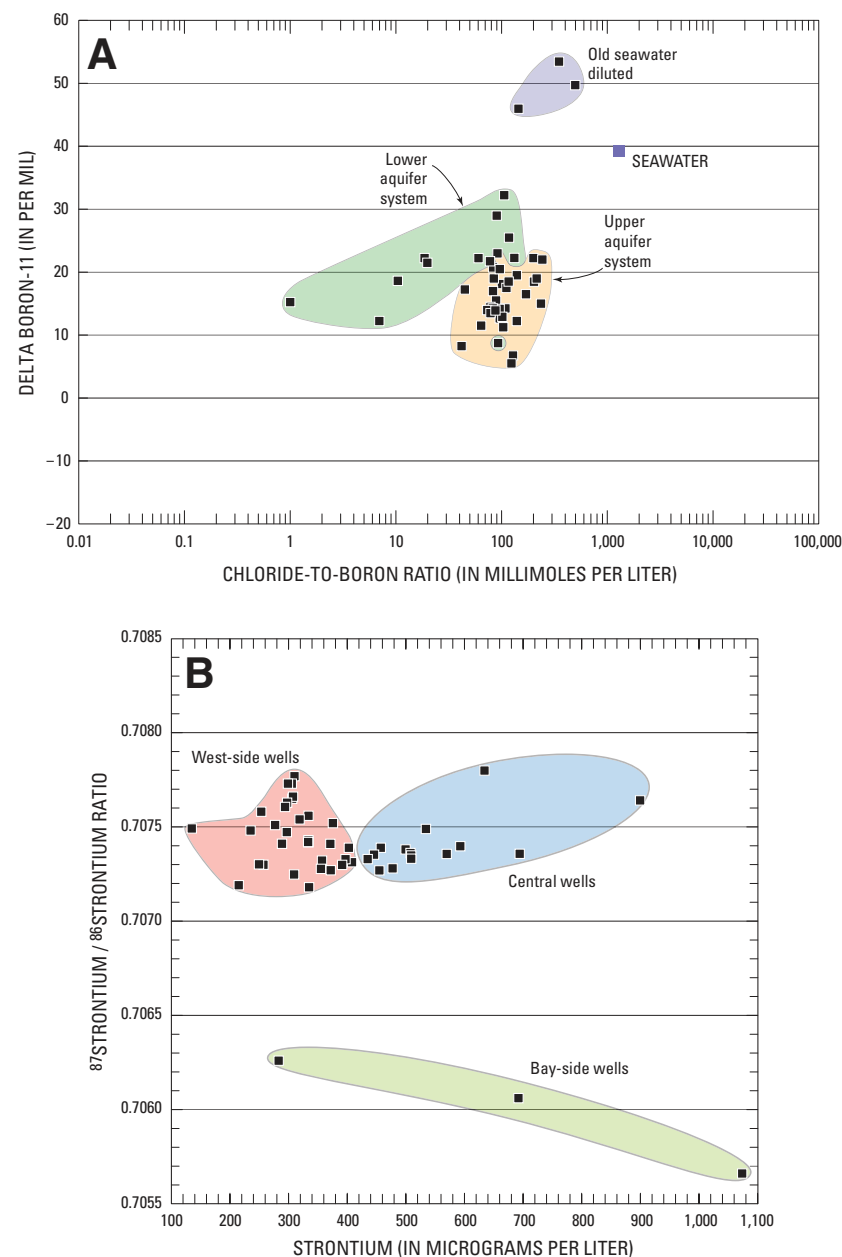


Figure 15. Graphs of (A) boron and (B) strontium isotopes for selected water samples in the Santa Clara Valley, California.

parts of the aquifer system result in water levels that can be more than 100 ft (30.5 m) below sea level. Thus, the potential for seawater intrusion under present developed conditions still exists and is most pervasive during droughts. In addition, some regions of the valley have poorer quality water that may represent older seawater or connate waters that have elevated chloride and sulfate concentrations. This includes the deeper aquifers in the Palo Alto region, as well as the older sediments in the Evergreen subregion. The inflow of saline water into the regional aquifers from the southern San Francisco Bay is retarded largely by the presence of the extensive Bay Mud deposits and completion of well screens below these deposits. There are few supply wells in the vicinity of the bay margin that would facilitate the movement of saline water through wellbore flow, as has been documented for other coastal basins such as the Ventura area (Hanson et al., 2003b). However, a sustained drought could increase the risk of seawater intrusion if levels of water pumping were maintained at seasonal lows for extended periods. Sustained drought also could increase the likelihood of importing water of lesser quality from increased salinity in the Sacramento–San Joaquin River Delta. This occurred in the droughts of the mid-1970s when delta water was too salty to be percolated into local aquifers but was still used by the water-treatment plants.

## WATER-RESOURCE MANAGEMENT ISSUES

Prior to the 1900s, most land in the Santa Clara Valley was used for cattle grazing and dryland farming. In the early 1900s, agriculture was the chief economic activity. As in most coastal basins in California, urbanization since the late 1940s resulted in the transfer of agricultural lands to residential and commercial uses. Since 1915, the population of the valley has grown from less than 100,000 to more than 1.7 million in 2000, with a 12.4% increase between 1990 and 2000 in Santa Clara County (U.S. Census Bureau, 2003). The Association of Bay Area Governments (ABAG) forecasts that Santa Clara County's population will increase nearly 35% by

2030, from 1,682,585 in 2000 to 2,267,100 people in 2030 (Santa Clara Valley Water District, 2006). Water use has changed from predominantly agricultural prior to the 1960s to almost completely urban and industrial water use since the mid-1960s. About 12.7 ft (3.9 m) of land subsidence and more than 200 ft (61 m) of groundwater-level decline occurred from groundwater development from the early 1900s to the mid-1960s. To mitigate the effects of groundwater depletion, surface water was imported for direct use starting in the 1950s and for artificial recharge in the mid-1960s.

Owing to the proximity to the San Francisco metropolitan area and the continued growth of the technology industries, growth may continue with an expanding urban and industrial economy. Accommodation of growth in the past few decades has been offset partly by conservation programs implemented by SCVWD and the local water purveyors. In addition, SCVWD has implemented an integrated water resource plan that seeks to balance water supply, flood management, and environmental stewardship of the water resources in the Santa Clara Valley (Santa Clara Valley Water District, 2003). While groundwater storage is not depleted permanently to meet demand during nondrought years, the projected increase in population and an improving economy will increase demand for water over the next 5 yr by 0.3% per year on average and increase by 1% per year on average after 2020 (Santa Clara Valley Water District, 2005). SCVWD has estimated that countywide water demand may increase by ~70,000 acre-ft (86.34 Mm<sup>3</sup>) or by 18% over the next 25 yr, even with increases in new water conservation efforts (Santa Clara Valley Water District, 2005). This would represent a 52% increase over the average pumpage from the period 1970–1999. SCVWD projects that beyond 2020, the county would start having groundwater depletion, and that by 2030, ~31,000 acre-ft/yr (38.24 Mm<sup>3</sup>/yr) of additional supply would be needed during nondrought years (Santa Clara Valley Water District, 2005). By 2030, SCVWD estimates that ~14,000 acre-ft/yr (17.27 Mm<sup>3</sup>/yr) of additional supply will be needed to meet demand during droughts (Santa Clara Valley Water District, 2005). This would represent between a 39%

and 58% increase in the average water supplied compared to the historical artificial recharge rate (1970–1999).

### Strategies for Controlling Subsidence

Subsidence is being controlled through the importation of water in lieu of groundwater pumpage. With groundwater levels almost as high as in the early 1900s, the potential for permanent land subsidence has been reduced substantially. However, the concentration of pumpage into well fields may sustain compaction over annual and dry climatic periods. This compaction would be predominantly elastic but may include some inelastic compaction. The direct use of imported water in lieu of pumpage and implementing smaller pumping rates over longer periods will help to further diminish the magnitude of the subsidence in and near these well fields. Preferably using wells that capture a larger percentage of artificial recharge also will reduce the storage depletion of the deeper aquifers and further reduce potential land subsidence. These strategies also will reduce the potential for differential subsidence, which may be critical for railways, highways, pipelines, and flood control. This potentially could affect the alignments for new projects, such as the potential southerly extension of the Bay Area Rapid Transit (BART) System down to San Jose. Any additional pumpage for export of stored water will need to account for the potential effects of differential subsidence from elastic and inelastic compaction. Increased artificial recharge to offset storage depletion from pumpage during interannual to interdecadal climate cycles will help reduce sustained declines that have driven more recent subsidence along the margins of the historic subsidence region.

### Conjunctive Use

Conjunctive use supply and demand components will need to be closely aligned with the three major climate cycles determined from the hydrologic time series of the valley. The cycles and lags estimated for the precipitation, streamflow, and groundwater levels suggest that planning for re-

lease of artificial recharge potentially could be enhanced by including these lags in the release schedules of artificial recharge into streams. For example, rejected recharge could be captured partially by accounting for these lags and increasing pumpage in selected well fields that would capture this stream infiltration prior to rejection back into the streams. Because multiple-aquifer wells potentially enhance the deep circulation of recharge, these wells also should be accounted for in the assessment of conjunctive use. In particular, multiple-aquifer supply wells that enhance recharge of the deeper aquifers should be evaluated carefully as part of the ongoing well-destruction program to see if these wells enhance recharge of deeper aquifers or may provide a conduit for VOCs and other anthropogenic contaminants. If extra groundwater in storage is exported, then additional artificial recharge through release of imported water in streams could be coordinated prior to these extractions to minimize the pumping lifts. However, the amount of recoverable groundwater from storage has multiple effects on conjunctive use and the regional water budget and, therefore, needs to be considered carefully in the management and development of water resources (Alley, 2006).

### *Future Sources of Water and Emerging Water Markets*

The management of water resources has evolved with changes in development of the valley. From early development of the water resources, the importation of water for direct use and artificial recharge occurred from the 1960s to the present. The SCVWD currently operates 10 reservoirs and 400 acres (1.62 km<sup>2</sup>) of spreading ponds that have helped not only to provide flood control but also to increase the reliability and sustainability of the water supply in the valley. The goal of refilling the aquifers was achieved during this period by SCVWD (Hanson et al., 2004b). However, the filling of the basin also introduces additional potential problems from high water levels, including return flow to streams, artesian flow through unsealed wells, and increased potential of liquefaction (Reichard and Raucher, 2003). With the basin filled after the last wet climate cycle, SCVWD currently seeks

to develop more cost-effective approaches to conjunctive use of the water resources that minimize these problems and that maximize the storage benefits of the groundwater system as protection against elevated demand during future droughts (Reichard and Raucher, 2003). With millions of dollars spent in capital improvements for water supply, flood protection, mitigation, and environmental enhancement by SCVWD, a reduction of costs and effective management of a sustainable water supply are required to maintain services (Santa Clara Valley Water District, 2006). Potential management alternatives may include shifting from maximizing artificial recharge to more direct delivery of surface water to users, exporting water to neighboring watersheds, or additional recharge facilities.

SCVWD also has initiated a regional consortium to help diversify the sources and storage of water, in order to increase reliability, reduce costs of the water resources, and decrease adverse effects from excesses or shortages of water, such as ties to the City of San Francisco distribution system, which obtains water from Hetch Hetchy Reservoir. As deliveries and storage of imported water in reservoirs and aquifers are further developed, there will be opportunity to develop water markets that include storing, trading, or selling water during certain periods within regional consortiums. For example, SCVWD has entered into a regional consortium on the southern watershed of the Pajaro River with neighboring water agencies that will allow water management options for both watersheds (Santa Clara Valley Water District, 2007). These regional consortiums further the diversity in the sources and storage of water such that there will be increased reliability and minimized cost of the water resources, along with fewer adverse effects from excesses or shortages of water.

## SUMMARY AND CONCLUSIONS

The hydrologic framework of the Santa Clara Valley in northern California was redefined on the basis of new data and a new hydrologic model. The regional groundwater flow systems can be subdivided into upper-aquifer and lower-aqui-

fer systems that form a convergent flow system within a basin bounded by mountains and hills on three sides and discharge to pumping wells and the southern San Francisco Bay. Faults also control the flow of groundwater within the Santa Clara Valley and subdivide the aquifer system into three subregions. The groundwater flow system also is affected by the presence of faults that may act as hydrologic flow barriers, by a subcropping bedrock high of serpentinite plunging northwest from Oak Hill, and by lithofacies that may represent regions of enhanced or reduced permeability. The regional groundwater flow system within the Santa Clara Valley also can be divided into two onshore subregions that represent the confined and unconfined parts of these aquifer systems. The alluvial aquifer systems are composed of a complex sequence of layers of fluvial sand and gravel and fluvial fine-grained silt and clay that represent eight glacial cycles of sedimentation over the past 718,000 yr. Each cycle represents a fining-upward sequence of predominantly fluvial and alluvial sedimentation that results in coarser-grained basal layers and fine-grained upper layers. These coarser-grained layers represent the aquifers, and the fine-grained layers represent the confining units or aquitards and less extensive interbeds. The water pumped as groundwater principally flows to the wells through the aquifers. The water that contributes to land subsidence mostly comes from the compaction of the aquitards. Correlation of geophysical logs indicates that there are six major aquifer layers in the valley. The aquifer layers are relatively flat lying and range from 10 to 200 ft (3 to 61 m) in thickness. The aquifer layers are separated by thin, low-permeability, fine-grained layers that result in as much as 10 ft (3 m) of vertical head differences between the layers. The effective base of the groundwater flow system ranges from ~500 to 900 ft (~152 to 274 m) below land surface.

After decades of development and groundwater depletion that resulted in substantial land subsidence, SCVWD and the local water purveyors have refilled the basin through conservation and importation of water for direct use and artificial recharge. The natural flow system has been altered by extensive development with flow paths toward

major well fields. Groundwater inflow occurs as recharge, subsurface flow along the northern coastal boundary of the southern San Francisco Bay, and water derived from aquifer and interbed storage. Groundwater outflow occurs as evapotranspiration, stream base flow, discharge through pumpage from wells, and subsurface flow to the San Francisco Bay. The changes in groundwater flow generally reflect the major climate cycles and the additional importation of water by SCVWD. Pumpage represents ~69% of the outflow from the groundwater flow system, and recharge had equal contributions from natural and artificial recharge during the period 1970–1999.

Climate cycles have not only affected the cycles of sedimentation during the glacial cycles over the past million years, but interannual to interdecadal climate cycles also have affected the supply and demand components of the natural and anthropogenic inflows and outflows of water in the valley. Since the late 1800s, six composite climate cycles that represent 14 wet and dry periods show variation that is collectively driven by the ENSO, monsoonal, and PDO cycles. Over 92% of the variation in precipitation is aligned with these cycles, and over 75% of the variation in groundwater levels is consistent with PDO-like cycles. Similarly, over 95% of the variation in streamflow is aligned with these climate cycles. The lags between precipitation, streamflow, groundwater levels, and climate cycles give some insight on how the flow system responds to climatic forcings. These lags can be employed as part of management strategies to enhance water supply sustainability as well as to schedule artificial recharge, pumpage, and potential exports.

Streamflow has been affected by development of the aquifer system and regulated flow from reservoirs as well as conjunctive use of groundwater and surface water. The decrease in groundwater pumpage generally has contributed to additional streamflow, as well as reduced recharge in upper reaches and more occurrences of larger base flows in the lower reaches. Streamflow gains and losses also covary with changes in groundwater levels. For example, the annual cycles of changes in groundwater levels generally lag behind the

changes in gains and losses by several months. Streamflow infiltration also may be affected by wellbore flow in supply wells near creeks.

Interaquifer flow through water-supply wells screened across multiple aquifers is an important component to the flow of groundwater in many developed aquifer systems. Wellbore flow and depth-dependent chemical and isotopic data indicate that flow into the well from multiple aquifers, as well as capture of artificial recharge by pumping of water-supply wells, predominantly is occurring in the upper 500 ft (152 m) of the aquifer system. Thus, the capture of artificial recharge from multiple-aquifer wells is an important part of the water-supply cycle in the Santa Clara Valley. The effects of wellbore flow within large water-supply well fields indicate that between 66% and 95% of the pumpage is derived from the upper-aquifer system, with major circulation occurring locally within the well fields through wellbore flow. The simulated intra-wellbore flow accounts for ~19% of the average net simulated regional groundwater flow, and for almost all interaquifer vertical flow, and it occurs in both pumped and unpumped multiple-aquifer wells. Thus, wellbore flow enhances deep recharge and, as such, supplies some of the water that otherwise would be simulated as water from aquifer and aquitard storage depletion in the lower aquifers.

Historic groundwater overdraft in the Santa Clara Valley caused up to 12.7 ft (3.9 m) of land subsidence from 1916 to 1969. Land subsidence can occur seasonally, over multiyear climatic cycles, or in response to long-term storage depletion from groundwater mining. An understanding of the distribution of compressibility estimates, relative to pumpage, as well as the spatial and temporal distribution of subsidence is critical to managing the water resources and minimizing the effects of land subsidence. Land subsidence since the 1980s predominantly is elastic and occurs over seasonal and climatic cycles, with extensometer data suggesting that most of the compaction occurred below the upper 250 ft (76 m) of sediments. These data are consistent with the typical range of well completions, wellbore flow measurements from supply wells, and thermal-gradient data from monitoring-well sites, which collectively indicate that most pumpage

occurs within the upper-aquifer system between 300 and 650 ft (91 and 198 m) below land surface.

Artificial recharge represents about one-half of the inflow of water into the valley for the period 1970–1999. Both imported water and local runoff are infiltrated through ~1.62 km<sup>2</sup> (~400 acres) of ponds and by direct release on selected streams. The percentage of artificial recharge ranges up to 61% for water-supply wells and up to 70% for monitoring wells, with the majority of the artificial recharge occurring down gradient of the recharge ponds on the western side of the valley. Thus, artificial recharge is an important part of the hydrologic cycle in the developed flow system and is being stored in the aquifers and captured by the water-supply wells for use during periods of increased demand.

Overall, the natural quality of most groundwater in the Santa Clara Valley is good. Major-ion chemistry demonstrates a relation of groundwater to recharge from local streamflow and imported water. On the basis of geochemical data, the source, age, and movement of waters in coastal aquifers generally can be subdivided into shallow and deeper aquifer systems. The major-ion chemistry suggests that mixing and other chemical reactions such as cation exchange, carbonate precipitation, sulfate reduction, silicate weathering, clay precipitation, and base exchange are occurring along flow paths. Wells from the central part of the valley appear to have different chemistry and may represent different waters from the deeper aquifers that may not receive recent streamflow or artificial recharge. Isotopic data indicate that artificial recharge is occurring throughout the shallower parts of the upper-aquifer system and that recent recharge (less than 60 yr old) occurs throughout most of the basin, but many of the wells in the center of the basin with deeper well screens do not contain tritium and recent recharge. Age dates indicate that the groundwater in the upper-aquifer system generally is less than 2000 yr old, and groundwater in the lower-aquifer system generally ranges from 16,700 to 39,900 yr old. Deeper aquifer systems also are subject to other water-quality issues in the southwestern part of the valley. For example, deeper sediments that contain serpentinous sediments may have additional trace metals that could

be subject to mobilization and alteration if exposed to oxygenated recent recharge through wellbore flow mixing. Overall, groundwater samples show a geographic partition into two groups that appear to represent wells on the west side and in the central part of the valley on the basis of strontium isotopes, which is consistent with the source and distribution of sedimentation.

Shallow aquifers not only contain more recent recharge, but they may be more susceptible to anthropogenic and natural contamination, as evidenced by trace occurrences of iron, nitrate, and VOCs in selected water-supply wells. Sources and depth distribution of nitrates may vary across the valley. Recent sampling for VOCs along several flow paths indicates different patterns and sources of trace amounts of VOC in the aquifers. These data also suggest that recent recharge can move and mix with existing groundwater through wellbore flow along the groundwater flow paths from the main recharge areas along the western side of the valley down into the confined parts of the aquifer systems.

Although the aquifers are bounded by the southern San Francisco Bay, earlier indications of some seawater intrusion along the margin of the bay are not present from recent evidence. However, the seasonal changes in groundwater levels in many parts of the aquifer system result in water levels that can be more than 100 ft (30.5 m) below sea level. Thus, the potential for seawater intrusion under present conditions still exists, and the potential is most pervasive during droughts with widespread water levels below sea level. Sustained drought also could increase the risk of importing water of lesser quality with increased salinity from the Sacramento–San Joaquin River Delta. Some regions of the valley also have poorer-quality water, which may represent older seawater or connate waters that have elevated chloride and sulfate concentrations. For example, the boron isotope signature and the ages of the groundwater monitoring wells in Palo Alto indicate these lower-aquifer system waters may represent older diluted seawater that was never flushed out of the deeper aquifers along the southwestern margin of the San Francisco Bay.

Water-resource management issues are centered on sustaining a reliable and a good-quality



source of water to the residents and industry of the valley. The evolution and growth of the water use, from agricultural to urban and industrial, continue from the early 1900s to today. The projected growth of the valley is more than 2.2 million inhabitants by 2030. Importation of water and conjunctive use of local surface water and groundwater are the sources of water to the valley. To mitigate the effects of groundwater depletion, surface water was imported for direct use starting in the 1950s and for artificial recharge in the mid-1960s, and conservation programs have been implemented. While the basin has been refilled, increased demand owing to growth and droughts could result in renewed storage depletion and the related potential adverse effects of land subsidence and seawater intrusion. SCVWD has implemented an integrated water resource plan that outlines balancing water supply, flood management, and environmental stewardship of the water resources in the Santa Clara Valley. Subsidence is being controlled through the importation of water in lieu of groundwater pumpage, but minimizing differential subsidence and seasonal and drought-related cycles may require optimization of pumpage distributions and pumping rates throughout the valley. Conjunctive use supply and demand components will need to be closely aligned with the three major climate cycles determined from the hydrologic time series of the valley. SCVWD also has initiated a regional association of water agencies that will facilitate additional diversity for potential sources of stored and imported water that can help to satisfy supply and demand on a regional scale and further reduce the adverse effects related to the magnitude and timing of replenishment and extraction of groundwater from the Santa Clara Valley. The projected increase in demand represents a 52% increase in pumpage by 2020. This increased demand would require about a 39%–58% increase in the water supplied for artificial recharge, or additional conservation and reuse.

The new hydrologic model demonstrates the importance of the aquifer layering, faults, and stream channels, in relation to groundwater flow and infiltration of recharge. The faults partially restrict groundwater flow from recharge areas and affect land subsidence driven by groundwater pump-

age. The shallow, coarse-grained stream-channel deposits are the main conduits to the center of the valley for natural and artificial recharge that occurs along the valley margins. Model results indicate that wellbore flow in wells screened over multiple aquifers is the main component of vertical flow between aquifers and is the main conduit for recharge to the lower aquifers. This model provides a means to analyze water resource issues because it separates the supply and demand components of the inflows and outflows by hydrologic components and spatially and temporally.

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#### REFERENCES CITED

- Alley, W.M., 2006, Another water budget myth: The significance of recoverable ground water in storage: *Ground Water*, v. 45, p. 251, doi:10.1111/j.1745-6584.2006.00274.x.
- Andersen, D.W., Metzger, E.P., Ramstetter, N.P., and Shostak, N.C., 2005, Composition of sediment from deep wells in Quaternary alluvium: *Geological Society of America Abstracts with Programs*, v. 37, no. 4, p. 91.
- California Department of Water Resources, 1967, Evaluation of Ground Water Resources, South Bay, Appendix A—Geology: *California Department of Water Resources Bulletin* 118-1, 153 p.
- California History Center, 1981, Water in the Santa Clara Valley: A History: *California History Center, De Anza College, Local History Studies Volume* 27, 155 p.
- Craig, H., 1961, Isotopic variation in meteoric waters: *Science*, v. 133, p. 1702–1703, doi:10.1126/science.133.3465.1702.
- Faure, G., and Powell, J.L., 1972, *Strontium Isotope Geology*: New York, Springer-Verlag, 188 p.
- Freeman, V.M., 1968, *People-Land-Water: Santa Clara Valley and Oxnard Plain*, Ventura County, California: Los Angeles, California, Lorrin L. Morrison, 227 p.
- Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., 2000, Measuring Land Subsidence from Space: U.S. Geological Survey Fact Sheet 051-00, 4 p.
- Halford, K.J., and Hanson, R.T., 2002, User's Guide for the Drawdown-Limited, Multi-Node Well (MNM) Package for the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Versions MODFLOW-96

and MODFLOW-2000: U.S. Geological Survey Open-File Report 02-293, 33 p.

- Hanson, R.T., 1989, *Aquifer-System Compaction*, Tucson Basin and Avra Valley, Arizona: U.S. Geological Survey Water-Resources Investigations Report 88-4172, 69 p.
- Hanson, R.T., 2003, *Geohydrologic Framework of Recharge and Seawater Intrusion in the Pajaro Valley*, Santa Cruz and Monterey Counties, California: U.S. Geological Survey Water-Resources Investigation Report WRIR03-4096, 88 p., <http://water.usgs.gov/pubs/wri/wri034096/>.
- Hanson, R.T., Wentworth, C.M., Newhouse, M.W., Williams, C.F., Noce, T.E., and Bennett, M.J., 2002, Santa Clara Valley Water District Multiple-Aquifer Monitoring-Well Site at Coyote Creek Outdoor Classroom, San Jose, California: U.S. Geological Survey Open-File Report OFR02-369, 4 p., <http://pubs.usgs.gov/of/2002/ofr02369/>.
- Hanson, R.T., Li, Z., and Faunt, C., 2003a, Application of the multi-node well package to the simulation of regional-aquifer systems in the Santa Clara Valley, California: *Modflow and More 2003, in Understanding through Modeling*, Conference Proceedings, 16–19 September 2003: Golden, Colorado, International Ground Water Modeling Center, p. 74–78.
- Hanson, R.T., Martin, P., and Kocot, K.M., 2003b, Simulation of Ground-Water/Surface-Water Flow in the Santa Clara-Calleguas Basin, California: U.S. Geological Survey Water-Resources Investigation Report 02-4136, 214 p., <http://water.usgs.gov/pubs/wri/wri024136/text.html>.
- Hanson, R.T., Newhouse, M.W., and Dettinger, M.D., 2004a, A methodology to assess relations between climate variability and variations in hydrologic time series in the Southwestern United States: *Journal of Hydrology (Amsterdam)*, v. 287, no. 1–4, p. 253–270.
- Hanson, R.T., Li, Z., and Faunt, C., 2004b, Documentation of the Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model, Santa Clara County, California: U.S. Geological Survey Scientific Investigations Report SIR2004-5231, 75 p., <http://pubs.water.usgs.gov/sir2004-5231/>.
- Hanson, R.T., Li, Z., and Faunt, C., 2005a, Hydrogeologic framework of the Santa Clara Valley, California: *Geological Society of America Abstracts with Programs*, v. 37, no. 4, p. 58.
- Hanson, R.T., Li, Z., and Faunt, C., 2005b, Simulation of subsidence for the regional-aquifer system in the Santa Clara Valley, California, *in* Zhang Aigen, Gong Shilang, Carbognin, L., and Johnson, A.L., eds., *Seventh International Symposium on Land Subsidence (SISOLS)*, Conference Proceedings, October, 2005, Vol. II: Shanghai, China, Shanghai Scientific & Technical Publishers, p. 616–627.
- Hanson, R.T., Dettinger, M.D., and Newhouse, M.W., 2006, Relations between climate variability and hydrologic time series from four alluvial basins across the southwestern United States: *Hydrogeology Journal*, v. 14, no. 7, p. 1122–1146, doi: 10.1007/s10040-006-0067-7.
- Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.
- Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land Subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437-1, 93 p.

- Iwamura, T.I., 1980, Saltwater Intrusion in the Santa Clara County Baylands Area, California: Santa Clara Valley Water District Report, 115 p.
- Jachens, R.C., Wentworth, C.M., Gautier, D.L., and Pack, S., 2001, 3-D Geologic Maps and Visualization—A New Approach to the Geology of the Santa Clara (Silicon) Valley, California: U.S. Geological Survey Open-File Report 01-223, 10 p.
- Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., Helley, E.J., Nicholson, R.S., Wright, H.M., and Brown, K.M., 2000, Preliminary Maps of Quaternary Deposits and Liquefaction Susceptibility, Nine-County San Francisco Bay Region, California—A Digital Database: U.S. Geological Survey Open File Report 00-444, version 1, <http://pubs.er.usgs.gov/publication/ofr00444> (accessed 2 April, 2014).
- Langenheim, V.E., Jachens, R.C., Wentworth, C.M., and McLaughlin, R.J., 2013, Previously unrecognized regional structure of the Coastal belt of the Franciscan complex, northern California, revealed by magnetic data: *Geosphere*, v. 9, no. 6, p. 1514–1529, doi:10.1130/GES00942.1.
- Langenheim, V.E., Jachens, R.C., Wentworth, C.M., Graymer, R.W., Stanley, R.G., McLaughlin, R.J., Simpson, R.W., Williams, R.A., Andersen, D.W., and Ponce, D.A., 2014, A summary of the late Cenozoic stratigraphic and tectonic history of the Santa Clara Valley, California: *Geosphere*, v. 11, doi:10.1130/GES01093.1.
- Leake, S.A., and Prudic, D.E., 1991, Documentation of a Computer Program to Simulate Aquifer-System Compaction Using the Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A2, 68 p.
- Mantua, N.J., 2006, The Pacific Decadal Oscillation (PDO) Index: Seattle, Washington, University of Washington Joint Institute for the Study of the Atmosphere and Oceans: <http://jisao.washington.edu/pdo/PDO.latest> (accessed 18 July 2006).
- Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production: *Bulletin of the American Meteorological Society*, v. 78, p. 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.
- Marks, N., Schiffman, P., Zierenberg, R., and Yin, Q., 2005, The origin of  $^{87}\text{Sr}/^{86}\text{Sr}$  in cold springs and travertines of the Franciscan Complex near Cazadero, California: San Francisco, California, American Geophysical Union, Fall Meeting, abstract V51B–1481.
- Muir, K.S., and Coplen, T.B., 1981, Tracing Ground-Water Movement by Using the Stable Isotopes of Oxygen and Hydrogen, Upper Penitencia Creek Alluvial Fan, Santa Clara Valley, California: U.S. Geological Survey Water-Supply Paper 2075, 18 p.
- Myhre, S.E., and Bencala, K.E., 1998, Surface-Water Quality Data, Permanente and Saratoga Creeks, Santa Clara Valley, California, Water Year 1997: U.S. Geological Survey Open-File Report 98-4, 39 p.
- Newhouse, M.W., Hanson, R.T., Wentworth, C.M., Everett, R., Williams, C.F., Tinsley, J., Noce, T.E., and Carkin, B.A., 2004, Geologic, Water-Chemistry, and Hydrologic Data from Multiple-Well Monitoring Sites and Selected Water-Supply Wells in the Santa Clara Valley, California, 1999–2003: U.S. Geological Survey Scientific Investigations Report SIR2004–5250, 134 p., <http://pubs.water.usgs.gov/sir2004-5250/>.
- Oze, C.J., LaForce, M.W., Wentworth, C.M., Hanson, R.T., Bird, D.K., and Coleman, R.G., 2003, Chromium Geochemistry of Serpentinous Sediment in the Willow Core, Santa Clara County, California: U.S. Geological Survey Open-File Report 03–251, 24 p., <http://geopubs.wr.usgs.gov/open-file/of03-251/>.
- Piper, A.M., 1944, A graphical procedure in the geochemical interpretations of water analyses: *Transactions of the American Geophysical Union*, v. 25, p. 914–923, doi:10.1029/TR025i006p00914.
- Poland, J.F., 1971, Land Subsidence in the Santa Clara Valley, Alameda, San Mateo, and Santa Clara Counties, California: U.S. Geological Survey Open-File Report, scale 1:125,000. [This precedes the time when open files were assigned numbers. Also released within jacket labeled “San Francisco Bay Region Environment and Resources Planning Study Technical Report 2.”]
- Poland, J.F., and Ireland, R.L., 1988, Land Subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497-F, 61 p.
- Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new stream-flow-routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, 95 p.
- Reichard, E.G., and Raucher, R.S., 2003, Economics of conjunctive use of groundwater and surface water, in Lawford, R.G., Fort, D.D., Hartmann, H.C., and Eden, S., eds., *Water: Science, Policy, and Management*: American Geophysical Union, Water Resources Monograph 16, p. 161–176, doi:10.1029/016WM10.
- Santa Clara Valley Water District (SCVWD), 2000, Relationship between Groundwater Elevations and Land Subsidence in Santa Clara County: Santa Clara Valley Water District: [http://valleywater.org/Water/Where\\_Your\\_Water\\_Comes\\_From/Local\\_Water/Groundwater/Subsidence.shtml](http://valleywater.org/Water/Where_Your_Water_Comes_From/Local_Water/Groundwater/Subsidence.shtml) (last accessed 25 April 2007).
- Santa Clara Valley Water District (SCVWD), 2003, Integrated Water Resources Planning Study 2003: Santa Clara Valley Water District: [http://www.valleywater.org/Water/Where\\_Your\\_Water\\_Comes\\_From/Water%20Supply%20Sustainability%20Planning/\\_pdf/2005-12-00\\_TLigon\\_IWRPStudy2003\\_Final.pdf](http://www.valleywater.org/Water/Where_Your_Water_Comes_From/Water%20Supply%20Sustainability%20Planning/_pdf/2005-12-00_TLigon_IWRPStudy2003_Final.pdf), (last accessed 25 April 2007).
- Santa Clara Valley Water District (SCVWD), 2005, Urban Water Management Plan: Santa Clara Valley Water District, [http://www.valleywater.org/Water/Where\\_Your\\_Water\\_Comes\\_From/Water%20Supply%20Sustainability%20Planning/Urban%20Water%20Management%20Plan/index.shtml](http://www.valleywater.org/Water/Where_Your_Water_Comes_From/Water%20Supply%20Sustainability%20Planning/Urban%20Water%20Management%20Plan/index.shtml) (last accessed 25 April 2007).
- Santa Clara Valley Water District (SCVWD), 2006, 2006/2007 5-Year Capital Improvement Program—DRAFT: Santa Clara Valley Water District: [http://valleywater.org/Water/\\_Capital\\_Improvement\\_Plan/2006-2007\\_plan/index.shtml](http://valleywater.org/Water/_Capital_Improvement_Plan/2006-2007_plan/index.shtml) (last accessed 25 April 2007).
- Santa Clara Valley Water District (SCVWD), 2007, Draft Pajaro River Watershed Integrated Water Resource Management Plan: Santa Clara Valley Water District: [http://www.valleywater.org/Water/Watersheds/\\_streams\\_and\\_floods/Watershed\\_info\\_&\\_projects/Uvas-Llagas/Draft%20Pajaro%20River%20Watershed%20IRWMP.shtml](http://www.valleywater.org/Water/Watersheds/_streams_and_floods/Watershed_info_&_projects/Uvas-Llagas/Draft%20Pajaro%20River%20Watershed%20IRWMP.shtml) (last accessed 25 April 2007).
- Stanley, R.G., Jachens, R.C., Lillis, P.G., McLaughlin, R.J., Kvenvolden, K.A., Hostettler, F.D., McDougall, K.A., and Magoon, L.B., 2002, Subsurface and Petroleum Geology of the Southwestern Santa Clara Valley (“Silicon Valley”), California: U.S. Geological Survey Professional Paper 1663, 55 p.
- Tolman, C.F., and Poland, J.F., 1940, Ground-Water, Salt-Water Infiltration, and Ground-Surface Recessions in Santa Clara Valley, Santa Clara County, California: *Transactions of the American Geophysical Union Fall Conference*, 1940, p. 23–35.
- U.S. Census Bureau, 2003, State and County Quick Facts: <http://quickfacts.census.gov/qfd/states/06/06085.html> (accessed 8 July 2003).
- U.S. Environmental Protection Agency (USEPA), 1994, Drinking Water Standards and Health Advisories: U.S. Office of Water EPA 822-b-00-001, 12 p.
- Wagner, D.L., Bortugno, K.J., and McJunkin, R.D., 1990, Geologic Map of the San Francisco–San Jose Quadrangle: California Department of Conservation, Division of Mines and Geology, Regional Geologic Map Series, Map 5A, 5 sheets.
- Wentworth, C.M., 1997, General Distribution of Geologic Materials in the San Francisco Bay Region, California—A Digital Database: U.S. Geological Survey Open-File Report 97-744, 27 p., <http://pubs.er.usgs.gov/publication/ofr97744> (accessed 2 April 2014).
- Wentworth, C.M., and Tinsley, J.C., 2005, Geologic Setting, Stratigraphy, and Detailed Velocity Structure of the Coyote Creek Borehole, Santa Clara Valley, California: U.S. Geological Survey Open-File Report 2005-1169, part 2, 01, 26 p., <http://pubs.usgs.gov/of/2005/1169/> (accessed 3 April 2014).
- Wentworth, C.M., Jachens, R.C., Graham, S.E., Graymer, R.W., Hanson, R.T., Mankinen, E.A., Tinsley, J.C., and Williams, R.A., 2004, Structure and Stratigraphy of the Santa Clara Valley: U.S. Geological Survey Open-File Report 2004-1424, 139 p.
- Wentworth, C.M., Williams, R.A., Jachens, R.C., Graymer, R.W., and Stephenson, W.J., 2010, The Quaternary Silver Creek Fault Beneath the Santa Clara Valley, California: U.S. Geological Survey Open-File Report 2010-1010, 50 p., <http://pubs.usgs.gov/of/2010/1010/> (accessed 2 April 2014).
- Wentworth, C.M., Jachens, R.C., Williams, R.A., Tinsley, J.C., and Hanson, R.T., 2015, Physical subdivision and description of the water-bearing sediments of the Santa Clara Valley, California: U.S. Geological Survey Scientific Investigations Report 2015-5017, 73 p., 2 plates, <http://dx.doi.org/10.3133/sir20155017>.